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## Retrospective analysis of dune change along selected beaches within the Wollongong LGA

Jack Daniel Talbert

*University of Wollongong*

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# Retrospective analysis of dune change along selected beaches within the Wollongong LGA

## Abstract

Dunes are the first line of defence against the physical forces of the coastal environment. Informed dune management is an important challenge for coastal managers, particularly with the predicted onset of rising sea levels. The measurement of long term trends and change in coastal systems can provide valuable information for informed and pre-emptive management of the world's coastlines. Methods commonly used for change detection involve retrospective measurement of the shoreline or high water mark using aerial photography. For more dynamic coasts however, longer-term trends in these features may be obscured by short-term fluctuations. In this study, three different methods for quantifying dune change using aerial photographs, photogrammetric data, and LiDAR data, are used. The methods include 1) dune volume calculation, 2) 2 m AHD contour movement analysis, and 3) vegetation line tracking. The techniques are applied to Woonona/Bellambi and Thirroul beaches located within the Wollongong Local Government Area. It is shown that the use of different indicators results in significantly different trend estimates and that caution must be exercised in the selection of appropriate indicators. For highly dynamic dunes, such as those at Woonona/Bellambi and Thirroul, indicators such as the 2 m AHD contour location and the dune volume provided a better indication of underlying trends in coastal erosion than the vegetation line. Woonona/Bellambi Beach was found to have accreted by 147,770.5 ( $\pm 60,000$ ) m<sup>3</sup> since 1961, while Thirroul appears to have fluctuated around its 1961 volume. A large storm cut of 76,719.8 m<sup>3</sup> was calculated for the whole of Thirroul Beach system after the 1974 storm events. An analysis of the methods highlights limitations, including a low temporal resolution, that should be addressed in future monitoring of dune behavior. The detailed analysis of dune change allows for more site specific management of the dune systems by Wollongong Council. This report provides an improved understanding of how the different systems have changed and can projected into future pre-emptive management.

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# **Retrospective analysis of dune change along selected beaches within the Wollongong LGA**

**Jack Daniel Talbert**



**A research report submitted as a requirement to fulfil the degree of  
Bachelor of Environmental Science (Hons)**



**School of Earth and Environmental Sciences  
The University of Wollongong  
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## Abstract

Dunes are the first line of defence against the physical forces of the coastal environment. Informed dune management is an important challenge for coastal managers, particularly with the predicted onset of rising sea levels. The measurement of long term trends and change in coastal systems can provide valuable information for informed and pre-emptive management of the world's coastlines. Methods commonly used for change detection involve retrospective measurement of the shoreline or high water mark using aerial photography. For more dynamic coasts however, longer-term trends in these features may be obscured by short-term fluctuations. In this study, three different methods for quantifying dune change using aerial photographs, photogrammetric data, and LiDAR data, are used. The methods include 1) dune volume calculation, 2) 2 m AHD contour movement analysis, and 3) vegetation line tracking. The techniques are applied to Woonona/Bellambi and Thirroul beaches located within the Wollongong Local Government Area. It is shown that the use of different indicators results in significantly different trend estimates and that caution must be exercised in the selection of appropriate indicators. For highly dynamic dunes, such as those at Woonona/Bellambi and Thirroul, indicators such as the 2 m AHD contour location and the dune volume provided a better indication of underlying trends in coastal erosion than the vegetation line. Woonona/Bellambi Beach was found to have accreted by  $147,770.5 (\pm 60,000) \text{ m}^3$  since 1961, while Thirroul appears to have fluctuated around its 1961 volume. A large storm cut of  $76,719.8 \text{ m}^3$  was calculated for the whole of Thirroul Beach system after the 1974 storm events. An analysis of the methods highlights limitations, including a low temporal resolution, that should be addressed in future monitoring of dune behavior. The detailed analysis of dune change allows for more site specific management of the dune systems by Wollongong Council. This report provides an improved understanding of how the different systems have changed and can projected into future pre-emptive management.

# Retrospective analysis of dune change along selected beaches within the Wollongong LGA

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## 1.0 Introduction

The Australian coastline presents itself as an exquisitely dynamic land area containing a plethora of human and natural environments. These include major cities and their reliant industries such as agriculture and tourism, as well as coastal wetlands, estuaries coral reefs and other habitats. 50% of the Australian population lives within 7 km of the shore (Chen and McAneney, 2006). All of Australia's major cities, excluding Canberra, are located in low-lying areas close to the coast. Furthermore, about 6% of the population resides within 3 km of the shore at elevations below 5 m (Nicholls et al, 2007). Historically, the residential and commercial infrastructure of the continent developed in vicinity of port facilities which were the central hubs of early 20th Century society (Cechet et al, 2011). It is clear that Australia's coastal zone has legacy of prominent development including vast and valuable infrastructure.

The coastal zone contains a variety of landforms ranging from sheltered, low energy deep bays and estuaries, to exposed, high energy sandy beaches occurring on open coasts (Short, 2012). NSW Coastal Policy (1997) defines the coastal zone as the area that extends one kilometre inland from the shoreline, including coastal rivers, lakes, lagoons, estuaries and islands, as well as 5.5 km seaward. There is approximately 29,900 km of coast bounding Australia, encompassing a vast array of beach types (Short, 2006). The coastline is considered among the most fragile and vulnerable natural environments (Mir-Gual, et al., 2012).

Fundamental to sustainable management of the coastline is a robust scientific knowledge of coastal spaces (Woodroffe, 2002). To enhance what is understood about the range of processes shaping the Australian coastal zone and to define the total behavioural environment of the system is a continual challenge for the coastal research community (McFadden, 2007). Current forecasts of climate change-induced sea level rise (SLR) (Lloyd *et al.*, 2012) is applying an unprecedented pressure on coastal researchers to provide a full understanding of the front line between the destructive physical forces of the dynamic coastline and our vulnerable and static socioeconomic infrastructure (Headland *et al.*, 2011). It is perhaps of no surprise that coastal research has undergone a paradigm shift away from the historic approach of applying a classification, or typology, to the coast as this provides few insights into management. Research is now directed towards an understanding that focuses on the process-dynamics through research aiming to recognize the mechanisms of change (McFadden *et al.*, 2007). The task of identifying the natural adjustments that underpin the dynamism of coastal

landforms is perhaps our strongest tool against the destructive potential of the coast's physical forces (McFadden, 2007).

The dune system is often the first barrier protecting the human legacy of development from destructive coastal processes (Evans and Hanslow, 1996; McFadden, 2007). An understanding of this active landform is paramount to allow for informed coastal management and future planning (Ranasinghe *et al.*, 2012). Dune morphology is highly dynamic and reacts to a range of coastal interactions (Houser, 2009). The dynamic coupling of hydrologic and morphologic interactions involves positive and negative feedbacks responsible for continual maintenance or modification of dune morphology (Woodroffe, 2002). Morphological changes occur through redistribution of sediment across the beach and dune system, primarily influenced by extreme storms and the height and extent of dunes relative to the elevation of the storm surge (Nott, 2006). When dunes are inundated, or considerably overtopped, they will be eroded vertically and the dune sediment will generally be redeposited inland to create a beach or dune ridge (Otvos, 2012).

There is an unavoidable amount of variability in storm characteristics (such as wind speed and incidence relative to the shore, and tidal stage during storm) that renders the response of dunes to individual storms highly unpredictable in nature (Anthony, 2012). A prominent example occurred throughout 1974 after a series of large storms caused extensive erosion along the southeastern coast of Australia (Bryant and Kidd, 1975). A profile monitoring program, running at Moruya Beach since 1972, was able to capture the erosive nature of these storm events and has allowed for quantitative insights into the reaction of the dune system to large storm events (McLean and Shen, 2006). Research similar to McLean and Shen is fundamental in assisting coastal managers with an improved understanding of beach morphodynamics.

To apply a morphodynamic approach to studying the coastal zone involves an understanding of both two-dimensional cross-shore relationships, and three-dimensional exchanges (Short, 2012). Two dimensional processes encompass shoaling and breaking waves, the surf and swash zone, antecedent topography, and beach face slope, whereas three dimensional processes includes beach responses to changing wave and tide conditions (Short, 2006). The accommodation of these processes within the morphodynamic approach to interpreting past and present beach conditions allows for an improved understanding of the changes occurring in beach systems. The morphodynamic approach is applicable to instantaneous events, similar to the cyclone events in 1974, through to processes occurring on geological time

scales, such as the mid-to-late Holocene shoreline recession along the South Australian coast (Sloss *et al.*, 2007). Explaining morphological phenomena using the morphodynamic approach has been championed in a range of studies since Wright and Thom (1977) first integrated ‘processes’ with ‘historical’ geomorphology. Beach morphodynamics specifically covers the physical interactions occurring within the interface between land and water along the coast. The Australian coast has been a prominent laboratory for investigating coastal systems and applying this approach since early beach system studies - pioneered by McKenzie (1956) (Short, 2012).

A common first step in explaining coastal systems involves classification based on similarities such as geological structure, sediment supply, wave climate, and tidal influence (Gomez *et al.*, 2007). Sanderson and Eliot (1996) classified a region of southwestern Australia ranging from Cape Arid to Cape Leeuwin. This specific classification was based on the occurrence and dimension of the coastal sedimentary landforms. Sanderson *et al.* (2000) built on the 1996 classification of the southwestern Australian coast and concluded that processes such as storm surge, wave diffraction, and long period water variations contribute significantly to the morphological evolution of sandy beaches and depositional landforms such as dunes along their study coastline. Furthermore, it was explained that due to these variations, the coast of southwestern Australia encompasses a heterogeneous reach of coast that receives a vast array of processes predominantly determined by wave refraction and diffraction processes, with little modification occurring from nearshore currents. This is valuable information for the management of this specific coastline.

The NSW coast contains highly settled and farmed estuarine plains in the north, smaller catchments and embayments in the south, and drowned river valleys within the Sydney Basin (Short, 2003). In contrast to the southwestern Australian coast, much of the NSW coastline is characterised by dense human settlement and development (Short and Woodroffe, 2009). The impacts of these anthropogenic modifications are the subject of much research and have led to a range of techniques, such as RTK-GPS and the ARGUS coastal imaging system, aiming to detect the changes that may be occurring and the influence of anthropogenic modification (Harley *et al.*, 2011; Tuner *et al.*, 2004; Hanslow, 2007). Detecting whether the beaches are receding (eroding) or accreting (through increased volume) is crucial for responsible management of the interplay between human development and the coastal environment.

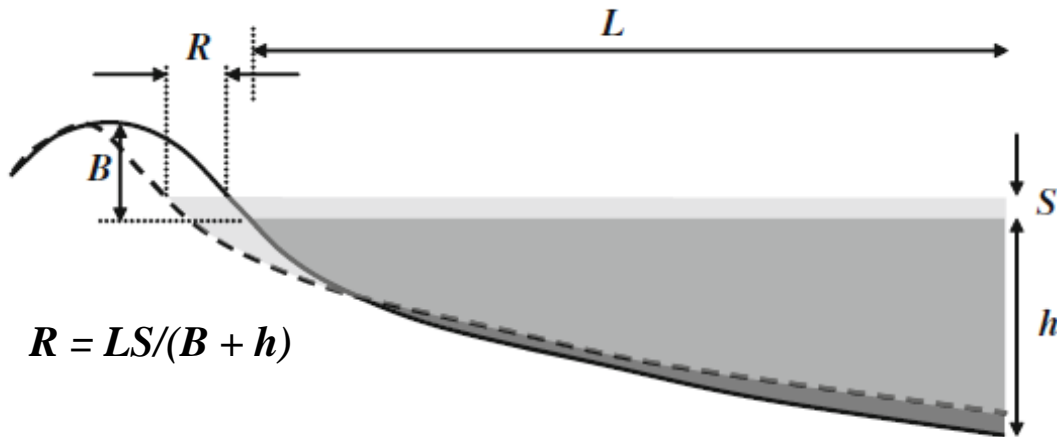
The vastly heterogeneous Australian coastline presents itself as an arduous area to predict and manage. Thus a case by case, or site specific, method of coastal zone management is a

necessity for coastal ecosystems and settlements. It is necessary that the extent of short-term beach fluctuations and historic longer term (decadal) trend in beach change are determined to allow for a responsible hazard assessment (Evans and Hanslow, 1996). Distinguishing the extremes of coastal recession allows coastal managers to draw hazard lines that act as boundaries for development along the coastline. Hanslow (2007) provides a review of the popular methods used to estimate historic beach recession using data gathered from remote sensors. He highlights that the vast majority of past papers that aim to determine beach recession have relied heavily on the shoreline as a reference feature. This is generally done by approximating the high water mark (HWM) from aerial photography. This change indicator is flawed due to the high degree of short-term variability of the HWM as it ranges significantly day to day. The true beach fluctuations may be masked by the dynamism of this indicator. Reasons for the HWMs variability include influences from the wind, beach slope, grain size, and the tide. Using the shoreline as an indicator should particularly be avoided where wave climate, beach slope, and beach variability is high, such as the east coast of Australia (Evans and Hanslow, 1996).

The challenge of measuring and predicting beach movement is further complicated by the impacts of a changing climate and sea level rise (Lloyd *et al.*, 2012). Sea level threatens to inundate coasts worldwide, with small island states being faced with complete inundation (Meehl *et al.*, 2007). It is further predicted that people living within areas prone to tropical cyclones will be faced with increased severity and increased frequency of these natural phenomena (Leibensperger *et al.*, 2012). It is estimated that approximately 6% of the Australian population lives within 3 km of shorelines in areas less than 5 m in elevation (Chen and McAneney, 2006). The latest sea level projections calculated by the IPCC (Meehl *et al.*, 2007) are in the order of 0.18 to 0.79 m by 2100 (compared to 1990). This predicted sea level rise will cause unprecedented coastal recession and threaten billions of dollars worth of coastal developments and infrastructure (Ranasinghe *et al.*, 2009).

The vastly diverse Australian coastline, whilst popular for morphological research, characteristically has highly variable coastal systems and thus equally varied management practices (Sanderson *et al.*, 2000). The current scientific context is yet to come up with a comprehensive understanding of the dynamic coastline to explain natural beach adjustments (Dora *et al.*, 2012). Coastal managers are consequently unable to solely rely on numerical modelling of beach behaviour at a high enough level of accuracy that allows for responsible coastline management (Ranasinghe and Stive, 2009). Historically, the method most

commonly used to estimate coastal recession due to sea level rise is a simple two dimensional principle known as the Bruun Rule (Bruun, 1962; Ranasinghe *et al.*, 2012). This is a mass conservation rule predicting a landward and upward displacement of the cross-shore sea bed profile as a response to a given rise in mean sea level (Figure 1).



**Figure 1: Schematic diagram showing the Bruun Rule for coastal recession (from Ranasinghe *et al.*, 2009)**  
[h = the maximum depth of exchange of material between nearshore and offshore, L = horizontal distance from the shoreline to depth h, B = berm or dune elevation estimate for the eroded area, S = sea level rise, and R = horizontal extent of coastal recession.]

Predicting coastal recession is of high importance due to the potential severe socio-economic losses that may occur due to sea level rise (Meehl *et al.*, 2007). The Bruun Rule has been routinely used by coastal scientists and engineers to predict coastal recession since its origin in the 1960s. This is despite a range of ambiguities and limitations having been highlighted, most recently, by Ranasinghe *et al.* (2012). Firstly, the rule is two dimensional, and therefore does not account for offshore sediment losses during storms, aeolian transport, backbarrier infilling and longshore interactions. Furthermore, it unrealistically assumes that wave climate is steady and that the beach equilibrium profile will stay the same as it moves landwards and upwards with the increase in sea level. It has been tried and tested and continually presents low quantitative accuracy due to, but not limited to, these shortcomings (Ranasinghe and Stive, 2009). Responsible coastal managers try to avoid the Bruun Rule when calculating the exact and site specific predictions of coastal recession caused by sea level rise, though there are few alternatives (Ranasinghe *et al.*, 2012).

Developing countries are the most vulnerable to the effects of climate change as they are often socially, technologically, and financially inept of adapting to the changes. On the other end of the scale are developed countries, such as the Netherlands, who are already adapting to the effects (Mulder *et al.*, 2011). Coastal inundation and erosion is of high concern to the

Netherlands due to its 9 million people living below sea level. It is therefore vital to the low-lying country that they protect their population through effective coastal erosion management. This objective is currently being achieved through the maintenance of the coastline's present location by adaptive human intervention via beach and shoreface nourishments (Jongejan *et al.*, 2012).

The continual development of a greater understanding of the total behaviour of the coast and the processes responsible for moulding the coastal system can result in more than just adaptive management (McFadden, 2007). Development plans that allow consideration of the coast to move with predicted long-term SLR has the potential to save coastal managers significant amounts of time and money. As McFadden (2007) states, "the effectiveness of coastal zone management is dependent on process-informed decision-making". Studies that allow for an understanding of future beach and dune conditions through a retrospective analysis of past coastal conditions can allow for such process-informed decisions to be made. Consequently, coastal studies aimed at quantifying longer term trends in erosion of the coastline of Australia are extremely valuable (Hanslow, 2007).

## **1.1 Aims and Objectives**

The broad aim of this report is to investigate and build upon the current body of research in circulation focussing on the management of the coastline, particularly that within the Wollongong Local Government Area (LGA). A review of relevant papers and reports was conducted and any priority areas of investigation were highlighted. This report has an emphasis on erosion/change measurement occurring at selected dunes within the Illawarra using three trend detection techniques. Consideration is given to beach morphology and condition within the study area. The use of remotely sensed data, predominantly photogrammetric- as well as LiDAR and photography, comprised the primary tools for providing dune trend and volume measurement.

The three methods applied to indicate changes across the dune system at Woonona/Bellambi Beach and Thirroul Beach are:

- a) dune volume analysis;
- b) 2 m AHD contour tracking; and
- c) Vegetation line movement.

Evaluation of these methods trends is conducted for Woonona/Bellambi Beach and Thirroul Beach. It is understood that the Woonona end of Woonona/Bellambi Beach is a current priority area due to questions and controversy associated with a decrease in beach width. Specifically, this report will focus on analysing dune change occurring at Woonona Beach and Thirroul Beach – and compare the change with reference to their distinct morphodynamics.

This report should provide assistance to coastal managers, engineers, and future researchers in assessing the morphologic conditions of certain beach types, and whether change detection techniques can or cannot be used to effectively calculate dune change. Specifically, the aim is to;

- Compile evidence of dune change at Woonona/Bellambi Beach and Thirroul Beach;
- Analyse the applicability of the three change indicators; and
- Generate recommendations for future beach monitoring and management along the southeastern coast of New South Wales, specifically within the Illawarra.

## **1.2 Thesis Outline**

Following this introduction is an overview of the available literature focusing on: the movement of sediment across coastal dunes and beaches; methods of monitoring this movement; current legislation in place to ensure safe and sustainable interplay between human and natural parameters in this zone; and an outline of Wollongong City Councils coverage of the coastal zone. The regional setting is discussed, followed by the report methodology, results, discussion and conclusion.



## **2.0 Literature Review**

The Australian coastline exhibits a diverse range of ever-changing landforms. It is a confronting task for coastal researchers and engineers to explain the processes operating and react to management issues associated with the coastal zone. For the purpose of this report - literature surrounding dunes and beaches are reviewed.

### **2.1 Australian Coastal Dune Systems**

There are over 10,000 Australian beaches surrounding the Australian continent (Short and Woodroffe, 2009). These beaches average 1.37 km in length (Short, 1993) with most being backed by some form of coastal dune system (Short and Woodroffe, 2009). The short length is due to enduring features such as bedrock, calcarenite and laterite, as well as rocks, reefs, and islands which act to bound and restrict the reach of Australian beaches. This geological inheritance acts on the dune systems by influencing sediment transport by directing the form of the beach shape, location, type, morphodynamics, and circulation (Short, 2010). Additionally, the transformation of wave energy across the shelf, nearshore, and surfzone also contributes to beach dune formation (Short and Hesp, 1982). It is apparent that dune systems have a multitude of processes contributing to their highly dynamic nature and defining their form (McLean and Shen, 2006). Short and Woodroffe (2009) interpret the location and formation of dunes to be the result of three factors: the beaches (the source of sand), the wind which transports the sand inland and the regional climate influencing the wind, as well as the dune vegetation and the ability of the dunes to stabilise.

A primary concern of coastal managers is to understand the active dune system for the purpose of safeguarding natural and human assets, including landscape, surf life saving clubs (SLC), houses and bike tracks residing in the coastal zone (Sanò, 2011). Studying the potential destructive ability of the unstable physical forces operating in the coastal zone can provide coastal managers with valuable information to manage this environment (McFadden, 2007). The dune is of particular importance as it is the first line of defence against coastal flooding and inundation.

Moruya, along the southeast coast, is one of the largest and most comprehensively-studied dune systems in Australia with an extensively developed hind-dune (Short and Woodroffe, 2009). McLean and Shen (2006) quantify the changes occurring at the berm, specifically, those that have lead to its formation. A beach profile monitoring program has existed at Moruya since 1972, continuing to this day, and has provided evidence of dune evolution. The

magnitude of volume change in McLean and Shen was effectively quantified for a 32 year time period of 1972 to 2004. The monitoring period captured the large storm events that occurred in 1974, as well as 1978. Subsequently the recovery events were also captured, allowing for an understanding of the coasts response to such large storms. Four morphodynamic phases were identified for the 32 year time period;

- Phase 1: 1972—1978: an erosional period with a high degree of beach change including an ADP (accretion dominated period) and EDP (erosion dominated period);
- Phase 2: 1978—1982: an incremental accumulation phase (ADP);
- Phase 3: 1982—1993: a relatively stable accretionary phase with small fluctuations;
- Phase 4: 1993—2004: a more variable phase with much large dune volume change.

The monitoring program by McLean and Shen (2006) has been able to provide valuable insights- both for geomorphologists and coastal managers- into the way the beach and dune acts under changing conditions. McLean and Shen have furthermore been able to quantitatively show that several conditions must be met to allow for the development of an incipient foredune at this beach; a berm being >2.3 m above MSL (mean sea level), have a width > 30 m, and a distance of > 30 m landward of the MSL intercept. These conditions have rarely been met at Moruya since 1972, but have persisted long enough for a foredune to develop, establish, and cut back when the conditions change. Studies and monitoring programs similar to McLean and Shen (2006) allow for valuable foresight into the management of the coastal zone as it increases coastal managers' ability to predict the direction of coastal movement under variable conditions.

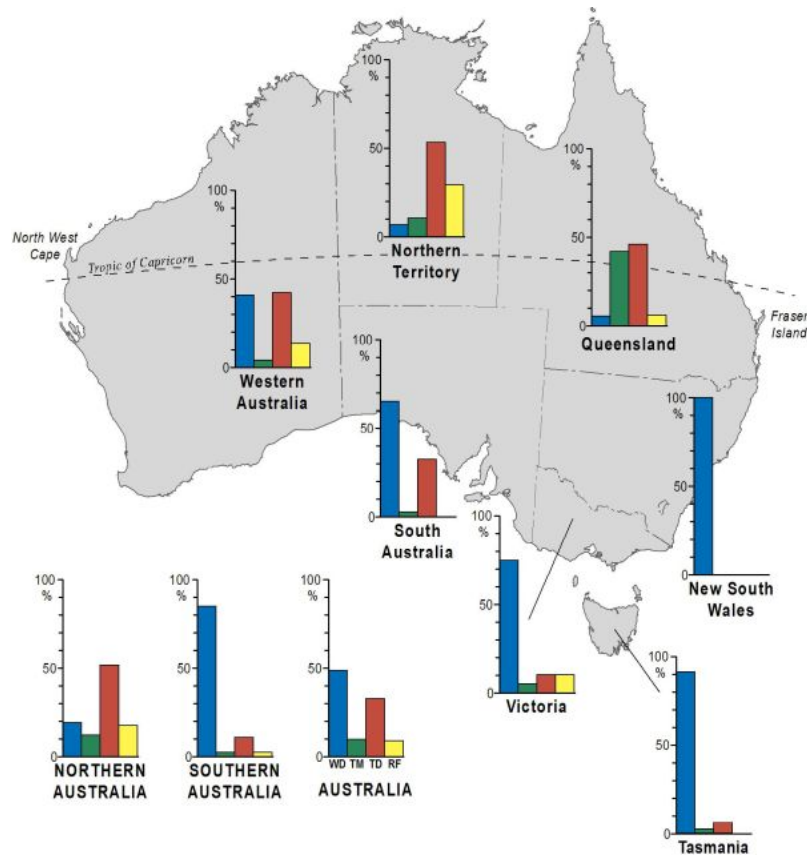
An understanding of dune morphology is fundamental for managing the changes that occur at the coastal zone- particularly in the advent of more changeable conditions of storminess caused by predicted climate change (Theuerkauf and Rodriguez, 2012). Benedet *et al.* (2007) evaluated hypotheses to explain the morphological variation at Delray Beach located on the southcoast of Florida based on an analysis of annual beach profile data. They researched the influence of: nearshore features (such as reefs) on nearshore propagation, variability of grain size alongshore, and changes in shoreline orientation induced by the placement of fill have on the development of erosion hotspots. Grain-size was found to have no relationship, while the shoreline orientation appeared to have the most significant influence on the amount of erosion. This was assumed to be due to an acceleration of alongshore currents and an increase in sediment transport potential at specific shoreline orientations. Benedet *et al.* conclude with a recommendation that bathymetric modifications that reduce wave obliquity at areas of high

erosion may reduce future volume loss. Studies of this nature are valuable to coastal managers, such as councils, as they allow for informed management. Furthermore, they increase the understanding of accretion/erosion processes occurring at the dunes.

Short and Hesp (1982) applied a method of morphodynamic classification of surfzones, beaches, and dunes along the microtidal, generally high energy southeast coast. They were able to provide distinctive likely sequences and extents of these environments based on the nature and characteristics of the dune forms and beach-surfzone. They concluded that at the time of their research there was still a great deal of work required before coastal managers can accurately model these environments. It has been 30 years since Short and Hesp's classification of wave, beach, and dune interactions, and accurate modelling of coastal environments is yet to come to fruition (Ranasinghe *et al.*, 2009). The inconvenient reality is that almost half of the Australian coastline is backed by dune systems (Short and Woodroffe, 2009). Filling in the remaining void of understanding that surrounds dune dynamics is of high importance for coastal managers.

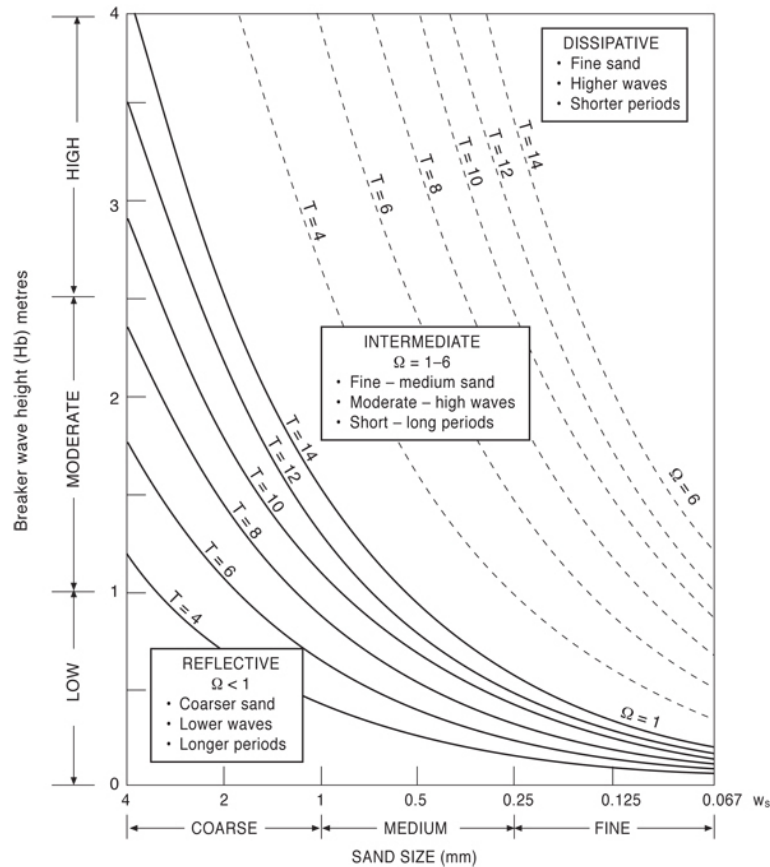
## **2.2 Australian Beach Systems**

The Australian coastline is vast and varied, containing 10,685 beaches (Short and Woodroffe, 2009). These beaches can be classified into 15 distinctive states based on the influence of waves, tides, and sediment. Specifically, there are six wave-dominated, three tide-modified, four tide-dominated, and two states controlled by intertidal rocks and fringing reefs (Short, 2006). The distributions of the four categories of beaches are shown in Figure 2. It is clear that New South Wales, and most of the southern coast is wave-dominated. This is mainly due to the region's exposure to persistent high energy Southern Ocean swells.



**Figure 2: Distribution of wave-dominated (WD: blue), tide-modified (TM: green), and tide-dominated (TD: red) beaches and beaches with rock/coral flats (RF: yellow). Note the dominance of wave-dominated beaches in NSW (Short, 2006).**

Along the open and higher energy south eastern Australian coast the beaches are classified as wave dominated (Short, 2006) due to a range of characteristic traits. The ocean swell has generally high waves with a mean significant height of 3 m, while the beaches are composed of fine to medium sands with a tidal range less than 2 m, which is generally never more than 1 to 3 times the average wave height (Short and Woodroffe, 2009). The coastal zone is at its most responsive along wave dominated sand coasts (Short and Hesp, 1982). Wave dominated beaches can be further categorised into six subcategories ranging from high energy dissipative, through intermediates, to lower energy reflective beach types. These sub categories are based on the wave size and sediment size, Figure 3 shows how beach type can be approximated from these two parameters. It is possible for a beach to move from one state to another as wave conditions change, thus the term ‘beach state’ is perhaps more useful, rather than ‘beach type’. Therefore, it is understood that subtle variations in the nature of wave height, sand size, and tidal range can greatly influence the state of beach.



**Figure 3: A plot to determine the approximate beach state for wave-dominated beaches by using wave height versus sand size, and wave period (from Short 1999)**

Dissipative beaches are the highest energy in the wave-dominated category. They will have a wide surf zone with shore parallel bars and channels, and generally shore normal circulation (Short and Hesp, 1982). A decrease in wave height and/or coarsening of sediment will create one of four intermediate rip-dominated beach types; longshore bar and trough (LBT), rhythmic bar and beach (RBB), transverse bar and rip (TBR), and low tide terrace (LTT). These intermediates characteristically have active rip circulation, crescentic-transverse bars and megacusps (Short and Hesp, 1982). The reflective beach is the lowest energy beach and is characterised by a barless surfzone, and steep and narrow beach (Short, 2006). This hierarchical classification of wave dominated beaches is outlined in Figure 4. Each beach type has a characteristic level of stability, zone of sediment storage, and mode of beach and dune erosion (Short and Hesp, 1982).

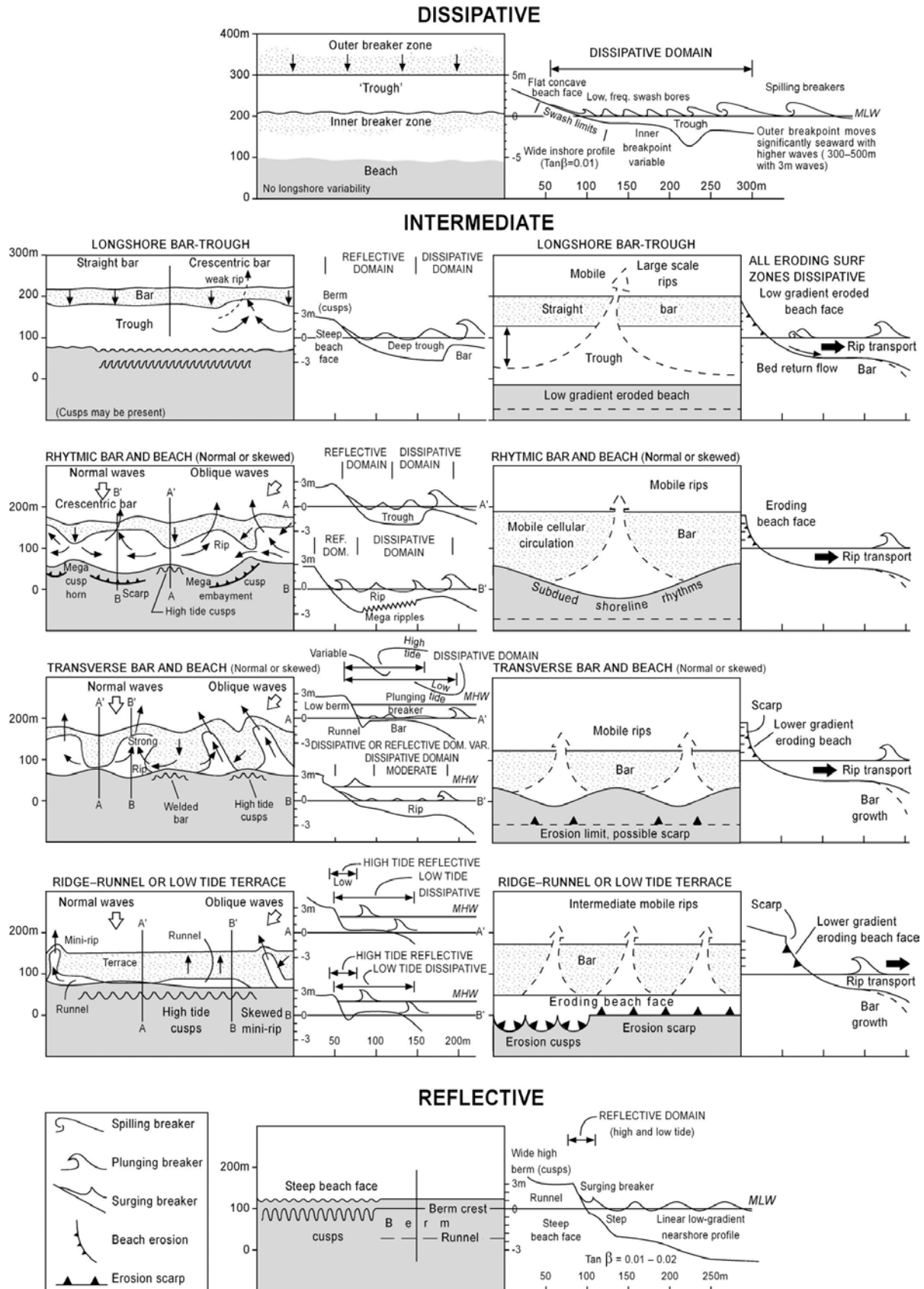


Figure 4: Wave-dominated beaches (from Short, 2006).

Short and Hesp (1982) pioneered the research into the relationship between waves, beaches, and the backing foredune and dune systems along the southern coastline of Australia. It was inferred that landward aeolian sediment transport of swash deposited sand is dependent on the beach topography and the wind acting across it. Observations taken across sections of the southern Australian coastline provided Short and Hesp with a ranking of the rate of aeolian sand transport occurring at each beach state. Rates are potentially highest on dissipative beaches, moderate on intermediate beaches, and lowest on reflective. These rates allow approximation of the potential size of foredunes, which are largest on dissipative and smallest on reflective beaches. This link is evident across the south eastern coastline as most of this reach experiences larger dune systems due to the high-wave and wind-energy (Short and Woodroffe, 2009). Within the Illawarra this link is somewhat masked by human development constraining the beaches, and the existence of small, embayed low energy beaches such as Fishermans Beach.

The findings of Short and Hesp's (1982) research into the major energy sources occurring at beaches set the benchmark for understanding the characteristic profile shapes for wave dominated beaches. Dissipative beaches can be expected to be characterised by large-scale transgressive dune sheets; while intermediate states will trend from large-scale parabolic dune systems where there is high-wave energy, to small scale blowouts where there is low wave energy. Reflective beaches will tend to have minimal dune development. They conclude that in evaluating the morphodynamics and evolution of sandy beach systems it is necessary to consider the contribution of the major energy sources: waves and wind.

Beaches and dunes alike provide researches with an ever-changing laboratory to investigate. As discussed above, both these landforms are clearly the subject of a vast array of interconnected directing processes. A primary objective of many coastal studies is to develop analytical procedures that quantitatively describe the changes occurring at the interface between the land, the sea, and the atmosphere. The following sub-chapter provides an account of various methods that have been applied by past researchers.

## 2.3 Monitoring Beach Change

It is difficult to assess the behaviour of a highly dynamic system such as a dune or beach (McLean and Shen, 2006). Unfortunately, this complex task is crucial to the understanding and management of the response of these environments to storminess and sea-level rise (Theuerkauf and Rodriguez, 2012). Various methods exist to quantify and explain changes in such systems. Aerial orthophotography is a common tool which allows for quantitative topographic photogrammetric analysis, however, there are limitations imbedded in the spatial resolution of topographic representations, their accuracy, and the temporal frequency of measuring events (de Vries *et al.*, 2012). Other possible geospatial tools to quantify beach change include real time kinematic—global positioning system (RTK—GPS) profile surveys, beach video analysis, and light detection and ranging (LiDAR).

Photogrammetric data is collected through the collation of accurate measurements from two overlapping vertical aerial photograph. This allows for high resolution digital data to be extracted and analysed in the form of spot heights. In NSW most data used to analyse coastal change is in the form of profiles, and has been the most commonly used tool for assessment of beach erosion and shoreline recession by the NSW Office of Environment and Heritage (OEH) (Hanslow, 1996). Deriving photogrammetric data from aerial photographs allows for retrospective topographic change detection as far back as the availability of high quality aerial photographs (Hanslow, 2007). However, there are uncertainties within this technique. End users of photogrammetric data have often been found to either overlook or not be provided with the numerous assumptions and variability inherent in the original photogrammetric data (Evans and Hanslow, 1996). Photogrammetrists estimate observation errors when compiling their data. These are based on the residuals between parameters including ground control and the model fit, as well as accounting for image glare, scale, and quality (Hanslow, 2007). It is crucial that these errors are considered, both vertically and planimetrically, when coastal researchers interpret inferred beach change from this technique. Hanslow (1996) acknowledges that to quantify beach erosion in the most valid way would require a long, frequently sampled, spatially dense, high quality record of past beach behaviour. Ground surveys taken at a high temporal frequency would be one such method. Alternatively an improved, detailed, comprehensive, and quantitative understanding of all processes affecting the dynamic coastal zone would allow for accurate modelling of beach evolution (Ranasinghe, 2009). Newer technologies such as LiDAR would allow for more accurate investigations into beach erosion trends, however, as this technology is relatively



new it cannot be used to gain a historical perspective on movement in the past (Theuerkauf and Rodriguez, 2012). Taking this into consideration, it is generally the case that when used correctly, photogrammetric analysis of historical aerial photography is a preferable option due its ability to provide a historic record. Pe’eri and Long (2011) provided a range of case studies in which LiDAR technology has been successfully used in concert with sonar and aerial imagery technologies as a valuable tool in coastal studies and management. In some cases it is possible to integrate a variety of methods (Mitasova, 2004). This collaborative approach is perhaps the best direction for future retrospective studies, though it is important to stay mindful of the inherent limitations in these technologies.

A reduction in the accuracy of photogrammetric data can be caused by a variety of factors (Table 1). Evans and Hanslow (1996) suggest that all too often coastal engineers do not account for various assumptions and variability inherent in photogrammetric data. Changes in vegetation are of most concern for the beach environment using this data type. Vegetation type, size, and density can skew the photogrammetric data on beach elevation. The data can mask the true evolution of the beach by recording the vegetation height instead of the surface elevation. Generally, to avoid this, for densely vegetated areas the photogrammetrist will plot ground level by drawing straight lines between points where the ground can be seen (Hanslow, 1996). It is imperative that this step is taken to avoid obvious systematic errors in the dune volume analysis.

**Table 1: Factors which limit the accuracy of photogrammetric data (adapted from Evans and Hanslow, 1996; Hanslow, 2007)**

| Limitation/ Error     | Description  |
|-----------------------|--|
| Photo Scale           | Data derived from large scale photography is likely to be more accurate compared to data derived from smaller scale photography.   |
| Lens Distortion       | Distortion due to the lens.  |
| Glare and Shadowing   | The photogrammetrist’s ability to accurately plot elevation is hampered by overexposed features, glare, and shadows cast by buildings, trees, or dunes. To avoid this problem, photography is limited to within two hours of midday. |
| Survey Control        | Ortho-rectification is not possible without good ground survey control. This is made much easier with modern GPS techniques.   |
| Changes in Vegetation | Vegetation type, size and density can mask the true topography of the dune system.   |
| Combined Errors       | It is generally accepted that the combination of above errors for photos post 1960 accumulate in $\pm 0.5$ m horizontally and $\pm 0.2$ m vertically. Errors may be locally higher where dense vegetation exists.                    |

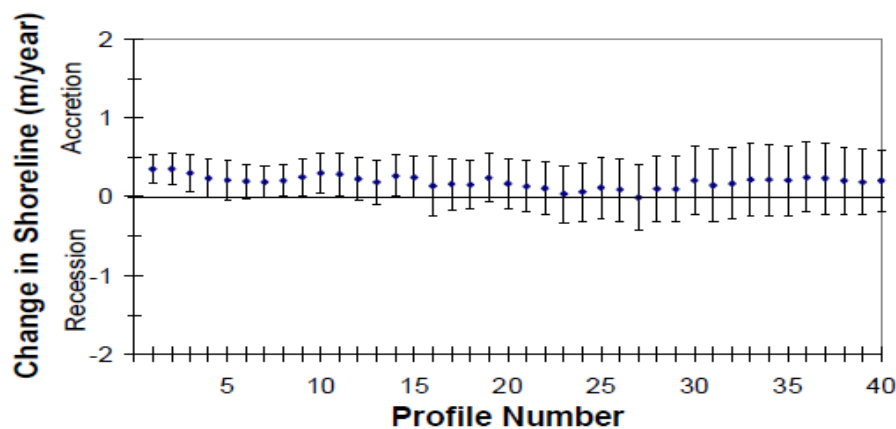
OEH provided photogrammetric data for Cardno (2010) to prepare a Coastal Zone Study for the Wollongong LGA. The photogrammetric data was processed to describe the 2 m AHD contour line from 1955 to 2007 to allow an estimate of active dune face movement, as well as quantifying dune volume change. AHD is the Australian Height Datum, which approximates mean sea level. It is unclear whether observation errors were accounted for in the photogrammetric data provided by OEH. The same photogrammetric data as used in Cardno (2010) has been re-analysed in this report and interpreted with the purpose of allowing comparison between the two, as well as to assess techniques of using photogrammetric data to assess dune change. The photogrammetry is developed from photographs taken between 1955 and 2007. For the past three decades OEH has funded the collection of photography of the NSW coast and applied it to a retrospective analysis of beach behaviour (Evans and Hanslow, 1996). The accuracy details for their photogrammetric data are outlined in Table 2. It is noted that the aerial photography post 1970 is from the OEH's Coastal Surveillance Program with photo scales between 1:8000 and 1:12000.

**Table 2: Estimated photogrammetric model accuracy based on rms fit and image quality (from Hanslow, 2007)**

| Date | Horizontal Accuracy (m) | Vertical Accuracy (m) | Quality |
|------|-------------------------|-----------------------|---------|
| 1955 | 1.5                     | 0.7                   | Poor    |
| 1961 | 0.5                     | 0.2                   | Good    |
| 1964 | 0.5                     | 0.2                   | Good    |
| 1972 | 0.5                     | 0.2                   | Good    |
| 1974 | 0.5                     | 0.2                   | Good    |
| 1987 | 0.5                     | 0.2                   | Good    |
| 1993 | 0.5                     | 0.2                   | Good    |
| 1999 | 0.5                     | 0.2                   | Good    |
| 2001 | 0.5                     | 0.2                   | Good    |
| 2007 | 0.5                     | 0.2                   | Good    |

The use of the shoreline as detected from aerial photography for a beach erosion indicator is another technique championed by previous studies (Anderson *et al.*, 2012). The shoreline is defined as the interface between the land and the water (NRC, 1990) and is the most commonly used indicator of coastal movement (Boak and Turner, 2005; Hanslow, 2007). Kane *et al.* (2012) applies a methodology for identifying chronic erosion threats to cultural assets along Hawaii's beaches by identifying erosion hazard lines based upon the shoreline change rates. It was found that the movement at various beaches could not be significantly distinguished from zero. This was likely due to the highly variable nature of shoreline change. The accretion and erosion periods as indicated by variations in the shoreline were very similar, therefore providing no indication of net movement.

The use of shoreline as a representative of beach change is disputed by Hanslow (2007). Similar to Kane *et al.* (2012), the method was found to lack statistical significance due to high standard errors in estimated rates of change at profiles being inherently high, in fact often being significantly larger than the calculated change (Figure 5). His research focussed on beaches along the central coast of south eastern Australia. This high standard error is most likely due to the shoreline interface being subject to short-term movement associated with physical processes such as swell, wind, waves, and beach slope. Boak and Turner (2005) assess the use of the shoreline as an indicator and conclude that the term *shoreline* can be as dynamic as the feature it defines.



**Figure 5: Rates of change in the shoreline at profiles taken at McMasters Beach (Hanslow, 2007). Error bars plotted correspond to the standard errors of each slope estimate.**

In Hanslow's (2007) comparison of beach erosion trend indicators conducted at McMasters Beach, the validity of the high water mark and vegetation line (among other indicators) in tracking beach movement is assessed. The HWW and vegetation line are identified off a series of georeferenced aerial photographs and movement is compared over years of available data. The HWM is similar to the shoreline indicator in that it is subject to high day-to-day variation due to short-term beach erosion and accretion, as well as other factors such as wind and wave conditions. Trends in the HWM were similar to using the shoreline marker—lacking statistical significance (Boak and Turner, 2005; Hanslow, 2007). Similarly, the vegetation line showed low levels of significance at best, which is most likely due to a lack of any movement at all at the study site. The vegetation therefore appeared to be acting independent of the changes in beach topography, suggesting that vegetation movement does not reflect the movement of the beach and dune system.

The most reliable trend indicators of long term coastal change appeared to be scarp location and sub aerial dune volume (Evans and Hanslow 1996; Hanslow 2007). Evans and Hanslow's comparative study found that both of these indicators provided statistically significant

findings towards the direction of movement of the dune system. Hanslow (2007) concludes that much caution should be given in selection of the change indicator. It is crucial to consider the geomorphologic variation in the indicators, as well as the measurement errors within them.

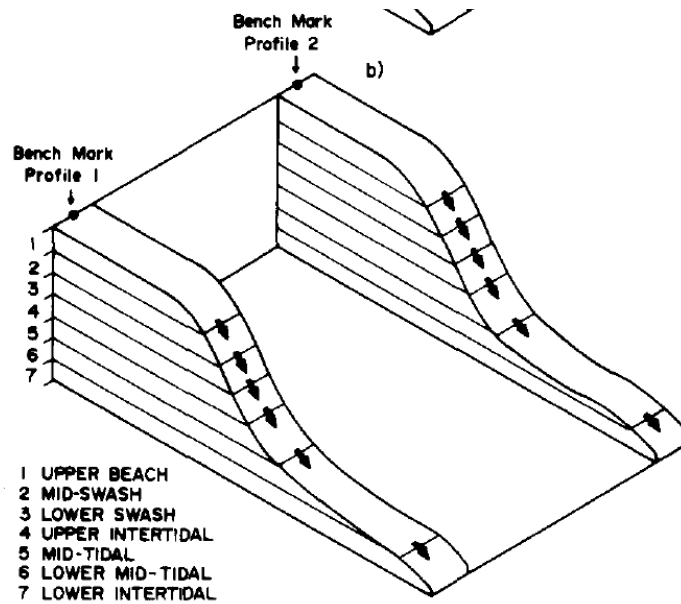
Real Time Kinematic-GPS profile surveying is a relatively new and highly accurate method of monitoring beach erosion. Theuerkauf and Rodriguez (2012) compared this very high spatial resolution technique against the use of only a limited number of profiles along a beach. The aim was to determine what distance between profiles is necessary to get a true indication of changes occurring within the entire beach system. RTK-GPS was found to be highly accurate when profiles were closely spaced across the beach, in fact each ~200 m long profile had ~4 million points of data with an estimated 3D error of  $\pm 3.0$  cm. When the number of profiles used across the beach was decreased, therefore increasing the space between profiles, there was a large decrease in the accuracy of the volume change calculated. It was further concluded that the amount of along-beach morphologic variability strongly affects the accuracy of beach profile surveys in monitoring volumetric change (less morphologic variation equates higher accuracy). It was suggested that the difficult task of choosing representative transect locations could increase the accuracy of the change detection. Theuerkauf and Rodriguez suggest avoiding locating transects along the horn or embayment of a beach cusp.

LiDAR is another modern geospatial technology that can be used to quantify change. LiDAR technology works through the use of a direct beam of radiation being emitted from a source, which reflects off a target, and bounces back to the source (a light sensitive semiconductor) where the response time is interpreted as directly proportional to the distance. Mitsova *et al.* (2004) apply its use in a study aiming to improve preservation and effective management of the largest active dune field on the east coast of the United States. Their goal was to use LiDAR to quantify the Jockey's Ridge dune deflation and horizontal migration. Similarly, Allen *et al.* (2011) applied the technology to the dune ridges along Cape Henry, Virginia. In both studies TINs (triangular irregular networks) were created from the LiDAR spot height to create a 3D model of the terrain. To allow for multitemporal interpretation it was necessary to integrate elevation data from historical geospatial data sets such as photogrammetric transects. Both Mitsova *et al.* (2004) and Allen *et al.* (2011) were able to produce a time series of 3D surfaces that allowed analysis of how specific coastal environments change over time. The successful use of LiDAR was able to provide valuable management insights. One

example was the ability to interpret which strategy had been most successful in slowing the dune migration, as well as what areas were eroding most rapidly and may be in need of stabilisation.

Long-term analyses of beach change involving frequent observations are notably rare across the Australian coastline (Thom and Hall, 1991). Bryant (1991) investigates a temporally extensive record of erosion and accretion for Stanwell Park Beach based upon an analysis of the HWM measured from oblique photographs spanning 1895-1980. The photos are dated to the nearest year and range from one every four years (1895-1920), one every two years (1920-1933), and more than one per year from 1933 onwards. They were analysed against sea level variations and rainfall records. Along the southeastern coast it is important that a high temporal resolution is used due to the characteristic seasonality in processes along this energetic and highly variable coastline (Short and Trenaman, 1992). Bryant concluded that there were a number of causal factors of beach erosion, stating that rainfall variation is a notable variable which can contribute to beach erosion and accretion. Specifically, Bryant estimated that when annual rainfall at Helensburgh exceeds 1635 mm, each 100 mm increment will cause 0.79 m of beach retreat from the HWM position. The accuracy of using photography and the HWM for beach movement has been disputed earlier in this chapter.

Clarke and Eliot (1988) conducted a study into the patterns of sediment movement along Warilla Beach, NSW. The methodology involved survey data for 18 profiles across the beach that were reduced to volumetric information for 0.5 m thick, horizontal slices of beach sediment. The horizontal slices approximated the upper beach, mid-swash, lower swash, upper intertidal, mid-tidal, lower mid-tidal, and lower intertidal zones (Figure 6). This temporal resolution allowed for identification of zones of maximum variability, linked with rip-current activity, as well as patterns of alongshore sediment movement in the swash zone. The study was compared to that of Clarke and Eliot (1982, 1983) where the profiles were analysed across 5 years only. Both studies at Warilla Beach revealed low-frequency beach changes, highlighting the need for long survey records to pinpoint long term change.



**Figure 6: Horizontal profile slices used to calculate specific zone volumes (From Clarke and Eliot, 1988).** It is a difficult and timely task to quantify the changes occurring along a beach or dune face. It is clear that previous literature has come up with a range of techniques that vary in accuracy. The trends and quantitative results of the various methods can inform and improve coastal management practices. The legislation informing management of the coast within the Wollongong Local Government Area is outlined in the following section.

## 2.4 Background Legislation within the Wollongong LGA

The legislation governing the coastal zone is continually changing, and should continue to do so parallel to improvements in the understanding of the coastal zone.

The *NSW Coastal Protection Act 1979* is the principal legislation relating to coastal management in New South Wales. The purpose of the act is to preserve and protect the coastal region whilst encouraging sustainable use. The *Environmental Planning and Protection Act 1979* placed the responsibility of safe coastal planning on local government. This is achieved through the provision of a framework outlining the requirements of a coastal zone management plan (CZMP). Conditions for preparing a CZMP are further outlined in the recently adopted *Guidelines for Preparing Coastal Zone Management Plans* (OEH, 2010). The *Guidelines for Preparing Coastal Zone Management Plans* provides specific instructions for producing a CZMP and replaces the previous guidelines found in the *Coastline Management Manual* (NSW Government, 1990). The main alteration was the adoption of a risk-based method of coastal management that provides a hierarchical, or prioritised, approach to coastal management. Similarly, the 1979 Act was amended by the *Coastal*

*Protection and Other Legislation Amendment Act 2010*. The OEH followed up the amended *Coastal Protection Act* with the *Coastal Protection Regulation 2011*.

During the preparation of this report, the NSW Government began a further review of *The Guidelines for Preparing Coastal Zone Management Plans*. A NSW ministerial taskforce was commissioned to undertake the review on the State's policy framework for coastal management. One of the outcomes of this review has been the removal of the NSW Sea Level Rise Policy Statement, and the requirement for councils to use the policy SLR benchmarks. The benchmarks were for 40 cm of SLR by 2050 and 90 cm by 2100 above 1990 mean sea levels (as used in Cardno (2010)). Individual councils are now advised to develop their own benchmarks for specific SLR. Marginalizing scientific knowledge has been discussed by McFadden (2007). Good governance relies upon the integration of the most up to date scientific understanding of the coastal environment.

As a result of the legislation development, the preparation of a CZMP was a strict requirement for all councils along the coastline of NSW. The integral framework of developing a CZMP has recently been completed by Wollongong City Council (WCC). The first step involved the council developing a Coastal Zone Management Committee, followed by the completion of a Coastal Zone Study (CZS). Wollongong City Council commissioned Cardno Lawson Treloar to undertake the CZS. The study was completed between June 2009 and May 2010. Cardno Lawson Treloar are a consulting firm whom specialise in environmental management, coastal and marine modelling and analysis, and water resources management, design and planning. The scope of the Coastal Zone Study covered the following elements;

- Site inspections across the study area consisting of the Wollongong LGA;
- Detailed studies of the coastal and geotechnical processes affecting the study area; and
- A targeted stakeholder consultation.

The key objective of the Cardno CZS was to characterise the coastal hazards affecting the Wollongong coastline so that accurate delineation of assets that were threatened by the hazards could be achieved. The study incorporates projected effects of SLR and changes in storm patterns brought about from the effects of climate change.

After the completion of the CSZ the preparation of a Coastal Zone Management Study and CZMP was necessary. Both were undertaken by engineering and environmental consultants

BMT WBM in the document *Wollongong Coastal Zone Management Plan: Management Study* (Rollason, 2012). The coastal management study allowed for consideration of all feasible management options whilst considering social, economic, aesthetic, recreational and ecological factors associated within the coastal zone. The key objective of the CZMP was to present management options for treating risks to assets and land along the Wollongong LGA's coastline, as well as providing a risk assessment, and risk treatment options, to manage the risks at each beach in the LGA.

The methods used in Cardno's coastal zone study are outlined in the following subsections.

## **2.5 Wollongong City Council CZS**

The following section outlines the comprehensive reporting conducted by Cardno (2010) on the Wollongong LGA coastal zone in the Coastal Zone Study.

### **2.5.1 Wollongong CZS Study Methodology and Data**

Cardno (2010) used a staged approach to quantify the coastal processes and hazards within the Wollongong LGA coastal area. This involved the following:

- A desktop review of existing hazard and coastal processes information;
- Determination of the major processes influencing the coastal region;
- Review of geotechnical investigations that relate to the study area;
- Quantitative investigations of the relevant coastal processes, specifically numerical modelling and analysis of photogrammetric data; and
- Determination of the coastal parameters for the 100-years ARI (average recurrence interval) design condition including wave parameters, design water levels and storm erosion, and water overtopping details.

### **2.5.2 Coastal Processes and Hazards**

The key physical coastal process and hazards acting on the Wollongong LGA coastline considered by Cardno (2010) are summarised below.

### **2.5.3 Wave Levels and Wave Climate;**

Cardno (2010) concluded that the study area is dominated by breaking wave conditions within the near shore zone at depths of 4 to 6 m. This led the study to use the Simulating



Waves Nearshore (SWAN) model to determine peak wave conditions at return periods between 5 and 100 ARI. It was found that along the Wollongong LGA coastline the critical wave direction is generally east-south-east. The term critical wave direction relates to the offshore wave direction that leads to the largest near-shore wave heights for a specified offshore wave height.

Considering the open nature of many of Wollongong's beaches, wave setup was considered an important component in the design water level observed at the shoreline by Cardno (2010). Wave setup is the increase in water level within the surf zone above mean still water level caused by the breaking action of waves. The water levels derived by Cardno were integral in defining the erosion and inundation hazards within the study area.

The study area includes cliffs and manmade structures such as sea walls. For this reason it was considered important to account for wave run-up. Wave run-up is the vertical distance above mean water level reached by the uprush of water from waves across a beach or up a structure such as a cliff or seawall. Wave run-up therefore plays an important role in cliff stability geotechnical and tidal inundation investigations.

The dominant direction of wave propagation and directional spread about that direction is defined by a Gaussian or generalised cosine distribution and a wave grouping tendency. The study did not incorporate directional spreading, or wave propagation, however, directional spreading was considered in the wave modelling process.

Wave data for the Cardno (2010) report was obtained from the Port Kembla tide gauge, and the wave rider buoy (WRB) at Long Reef in Sydney. Cardno (2010) have shown a high level of correlation (Appendix A) for offshore wave conditions between these two locations. For Cardno (2010) the Port Kembla tide gauge provided the wave height data, while wave directions were derived from measurements taken at the Long Reef WRB.

#### **2.5.4 Tides and Water Levels**

Water level records obtained from the Port Kembla tide gauge allowed for tidal planes to be derived. These tidal planes were applied to the whole study area. The study area tides are semi-diurnal with a significant difference between successive high and low tides.

Extreme water levels were taken from the Fort Denison tide gauge. They exclude wave set up and relate to locations seaward of the breaker zone. Cardno (2010) considers there to be negligible difference between offshore locations at the study area and Fort Denison, for

example, both locations have full open coast tidal range conditions. Table 3 displays the extreme water levels at various ARIs.

**Table 3: Extreme Water Levels at Fort Denison (DECCW, 2010)**

| ARI (years) | m LAT | m AHD |
|-------------|-------|-------|
| 10          | 2.27  | 1.35  |
| 20          | 0.3   | 1.38  |
| 50          | 2.34  | 1.41  |
| 100         | 2.36  | 1.44  |

### 2.5.5 Modelling

Cardno (2010) applied a range of modelling techniques incorporating the above parameters.

### 2.5.6 SWAN

Simulating Waves Nearshore (SWAN) is a numerical model that computes random, short-crested wind-generated waves in coastal regions and inland waters. It accounts for a comprehensive variety of physical parameters including wave propagation, shoaling, refraction due to current and depth, frequency shifting due to currents, and wave induced setup. The output generated by SWAN is one and/or two dimensional and computes wave height, period, direction, directional spreading, set-up, diffraction, and wave-induced force.

The SWAN model used in Cardno (2010) covered an area approximately 12 km offshore, beyond the 100 m depth contour. A 100 m grid was extended over the Wollongong coastline with eleven 10 m grids extended over the beaches and headlands of the Wollongong region within the 100 m grid overall model. The SWAN output was described by Cardno (2011) as achieving good calibration with offshore Port Kembla wave data.

### 2.5.7 SBEACH

Storm-induced Beach Change (SBEACH) modelling was also applied to allow for investigation into storm erosion at individual beaches within the Wollongong LGA coastal area. SBEACH is a numerical model developed by the US Army Corps of Engineers to allow for estimation of erosion of the beach, berm, and dune by storm waves and sea level rise (Wise *et al.*, 1996). In the Cardno (2010) study the model was used to describe beach by beach variation in storm bite to a 1 in 100 year erosion event for the beach at highest exposure to wave energy/storm bite within the study area.

Rollason (2011) suggests that SBEACH is not an appropriate tool to estimate storm erosion for planning purposes at beaches under certain conditions. Specifically, Rollason questions the use of SBEACH if the shoreline accretes, recedes, or rotates by longshore transport processes, or cross-shore processes, interacting with coastal structures and headlands. The lack of accounting for longshore processes results in a significant underestimation of erosion. This is embedded in the limitation of treating a beach as a 2D profile, similar to the Bruun Rule. For example, a storm arriving from an oblique direction will generally transport sand from the protected end of the beach and be deposited at the opposite, impacted end of the beach via longshore transport. Ranasinghe *et al.* (2004) outlines this process along the southern and central coastline of New South Wales and link it with the Southern Oscillation Index (SOI). Their results indicated that during El Niño phases the northern end of the beach will accrete, whereas during La Niña phases, the opposite occurs, resulting in a net clockwise rotation of the beach.

SBEACH assumes that the beach profile results only from cross-shore processes with no net gain or loss of material, but rather, only redistribution of sediment. Wise *et al.* (1996) supports this assumption for short-term storm-induced profile response on open coasts away from coastal structures and tidal inlets. It is unclear whether beach rotation and longshore transportation exists along Wollongong beaches, therefore caution should be taken when considering the use of SBEACH along these beaches.

### **2.5.8 Delft3D**

The Delft3D Flow hydrodynamic modelling system was adopted for wave inundation investigations. This model was used for its proven ability (Elias *et al.*, 2000) at simulating various processes such as water levels and longshore and cross-shore currents with suitable confidence.

Delft3D comes in a variety of models that allow for simulation of various two-dimensional and three-dimensional flows, sediment transport and morphology, waves, water quality and ecology, and the interactions between these processes. Cardno (2010) used Delft3D to specifically simulate non-steady flows in relatively shallow water, therefore simulating the likely conditions that inundation along the Wollongong coast would create. The model incorporates the interactions between tides, winds, air pressure, density differences, waves, turbulence, and drying and flooding.

Cardno (2010) applied the model by overlaying grids over various beach compartments within the study area. Generally, the grids covered a landward extent starting from the erosion hazard line to beyond the 10 m AHD contour.

#### **2.5.9 Data Collation**

Accurate data was necessary to allow the use of the numerical model systems.

#### **2.5.10 Geospatial Data**

A Digital Elevation Model (DEM) was constructed for the study area. It relied on a range of data sources including LiDAR data provided by Wollongong City Council, hydrographic charts from the Australian Hydrographic Office, and a hydrographic survey conducted of Wollongong Harbour. The available data was unfortunately sparse in some areas such as unsurveyed shelf reef sections. Because of this, contour lines were estimated in these areas qualitatively from aerial photography and site observations. This created a degree of uncertainty in the nearshore bathymetry, particularly in between Bellambi Point and Stanwell Park where the hydrographic information available was limited.

#### **2.5.11 Geotechnical Data**

Underlying rock layers and hard clay along a coastline will act as a limiting factor in storm induced erosion. It is therefore necessary to determine the location and extent of underlying rock layers within the beach compartments to improve storm bite estimates.

A geotechnical investigation was conducted in October 2009. Twenty-three test pits were excavated on twelve beaches. All but four test pits were excavated to a maximum reach of 3.5 m or practical refusal due to pit collapse. The four remaining pits provided information on encountered boulder armour layers (Wombara and Sharkies Beach), natural residual sandstone clay layers (Sandon Point Beach), and lithic sandstone bedrock (Bellambi Point). This allowed for improved storm analysis as it infers limiting extents for storm bite.

One sample from each beach was obtained and sent to the laboratory for testing of particle grading. The sediment grain size was inferred from the results for each beach and applied to the storm bite modelling through SBEACH.

### **2.5.12 Monitoring Beach Change**

Additional to modelling, the historical beach change was inferred through the use of photogrammetric data supplied by OEH for 11 beaches within the study area. An analysis of dune profiles was conducted to determine changes across the years of photography (1955-2007). It was concluded that at the time of the study there was no evidence of long term shoreline recession or loss of beach volume in the Wollongong LGA. The method of identifying volume change conducted by Cardno was through the analysis of change in volume at selected profiles and the movement of the 2 m contour. The photogrammetric analysis conducted by Cardno (2010) provided various results including the minimum beach volume being that observed in the 1974 profiles. This is consistent with expectations based on storm conditions occurring at this time (Bryant and Kidd 1975).

This report will provide further and more detailed information on Woonona/Bellambi Beach and Thirroul Beach using similar data to Cardno (2010). The aim is to allow for more site specific interpretations of sediment movement and dune change whilst taking into account the morphology and surrounding environment of the two beaches. The end goal is to increase the potential of informed management of the beaches within the Wollongong LGA.

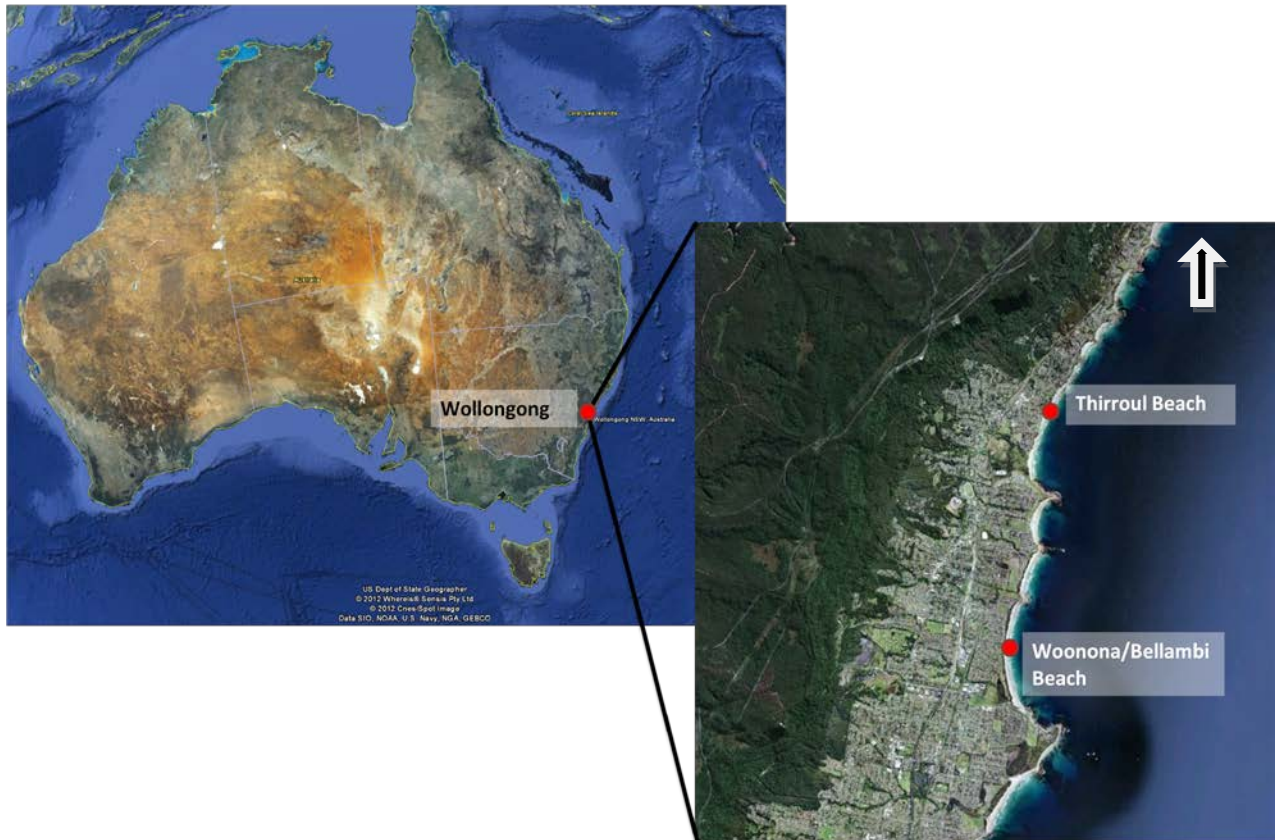
## 3.0 Regional Setting

### 3.1 Study Area

The study area under consideration in this report is located along the coastline that lies within the Wollongong LGA—restricted to the coastal zone extending from Lake Illawarra northwards to the Garie Beach. The coastline of Wollongong (34°25'S) is located on a pericontinental (continent surrounding) shelf on the passive margin of south-eastern Australia. It is noted to be narrow (<30 km) and steep (Wright, 1995). The inner shelf (0 to 60m) is covered by well rounded, well sorted medium to fine grained terrigenous quartzose sands and some calcareous debris (Griffin et al, 2008). The beaches throughout Wollongong were formed by shoreward movement of sand and barrier construction during higher sea-level phases. The sediment is likely to have been derived from the continental shelf where deposition from coastal rivers had taken place during periods of lower sea level (Bryant, 2007).

The Wollongong coastline consists of exposed beaches that receive moderate southeast swells over 2 m and tides less than 2 m and is generally wave dominated (Short and Woodroffe 2009). The southern ends of Wollongong's beaches tend to be more protected than their adjoining northern end due to the direction of swells and the existence of headlands and therefore experience a lower energy environment (Clarke and Eliot, 1988). The beaches are semi-compartmentalized, exposed, sand-starved and usually dominated by bedrock reefs near bounding headlands (Bryant 2007). Due to the prominent structural control some of the beaches are often forced into an abnormal looking morphology (Bryant, 1981) such as Fishermans Beach in Port Kembla.

Specifically this report will analyse and compare changes occurring within the dunes at Woonona/Bellambi Beach and Thirroul Beach (Figure 7). Historically, both beaches have undergone some large-scale anthropogenic modification. Thirroul Beach has a swimming pool in its centre that in the past would pump its water onto the beach. It also has as a shore-normal sea wall. Both of these human influences are likely to have caused increased erosion. Woonona/Bellambi Beach has had construction sand extracted in the last century, with an unknown amount of erosion caused (Bryant, 1981). It is also noted that the councils initiated a vegetation establishment and management plan in 1986 to stabilise and restore the natural function of damaged dune systems along Australian beaches (Bernd-Cohen and Gordon, 1999).



**Figure 7: Study locations.** *Source:* “Wollongong, Australia.” 34°55′24.47″S and 150°55′24.47″E. Google Earth GeoEye. September, 2012.

Short (1993) provides descriptions of the physical characteristics for the beaches used in this report. His descriptions were based on the results of the NSW section of the Australian Beach Safety and Management Program and are summarized below.

### **Woonona/Bellambi**

Woonona/Bellambi Beach is considered to be in an intermediate state, generally acting as a transverse bar and rip (TBR) at the Bellambi (southern) end and a transverse bar and rip/rhythmic bar and beach (TBR/RBB) at the Woonona (northern) end. The open beach is 2 km long with Bellambi Creek and a low foredune located at most of the southern back beach and with vegetation between the dune face and hind dune development. The southern point of the beach extends seawards and shelters the southern end of the beach which faces north east. Woonona generally receives waves averaging 1 to 1.5 m, and usually has an attached bar cut by rips every 200 m with a permanent rip against the northern rocks. The Bellambi end of the beach has a smaller wave height due to the protection provided by Bellambi Point, averaging 0.5 to 1 m. In summer the waves can be higher, averaging between, 1 and 1.5 m, due to the summer north east waves and winds. The Bellambi end usually has an attached bar with a decreased rip frequency and intensity compared to the northern beach end.

## **Thirroul**

Thirroul Beach is predominantly in a TBR and RBB state, however, beaches can be in other states after unusual wave events. The beach is a 1 km long open beach and faces east south east (Figure 7). It is separated from its adjacent beaches by rock platforms and low bluffs at the north and south respectively. Waves at Thirroul Beach average 1 to 1.5 m producing a single bar usually cut by 6 rips. Transient rips exist across the beach, while permanent rips exist at the northern and southern rocks. Most of the back beach is not vegetated, apart from grasses. There is a small inlet in the centre of the beach.

## **3.2 Study Area – Coastal zone Management Plan**

Both the Cardno (2010) CSZ and Rollason (2011) CZMP adopted a definition of their study location to include only the coastal zone within the Wollongong LGA. It is noted that Port Kembla port area, and areas managed by the NSW Office of Environment and Heritage (OEHS) National Parks and Wildlife Services were excluded (such as the Royal National Park and the Five Islands Nature Reserve).

Rollason (2011) further specified the study area as including all locations within the LGA that covers the interaction of coastal environments such as beaches, bluffs, and coastal entrances that will have future management affected by both coastal processes and hazards and human activities. The study area includes public lands and private lands- predominantly residential, with some commercial and industrial uses.

Broker and Mangor (2011) use the term “working with nature” when discussing the goal of obtaining overall sustainable development. Unfortunately the Wollongong coastline was not originally developed with what would now be considered appropriate consideration to natural phenomena occurring at the coastal zone. There is now a more informed understanding within the scientific literature of the processes occurring at the transition area from land to sea. These processes include forces such as tides, surges and waves, sediment transport, erosion, and sand accumulation. The impacts of these forces are further exacerbated as they combine with the influences of climate change visible in the form of sea level rise and changing wind and storm patterns. As a result of the legacy of development within Wollongong- the interactions between coastal processes and shoreline development is the fundamental cause of concern for hazard management within the coastal zone of the Wollongong LGA.



### 3.3 1974 storm Event

The 1974 storm conditions had a considerable effect on the New South Wales coastline and can provide valuable information on the impacts of future large storms within Wollongong. There were three periods of erosive wave events that had a compounded impact on south-eastern Australian beaches (Bryant and Kidd 1975). These periods were characterised by high-energy waves with a wave period of 8-9 seconds occurring on May 27<sup>th</sup>, June 4<sup>th</sup>, and June 14<sup>th</sup>. The meteorological conditions that created these storm conditions involved the following factors:

- Winds set up by a recurring pattern of pressure events involving the development of an extra-tropical low pressure system occurring over the western Tasman Sea, and an eastwardly migrating Antarctic high pressure cell across the Great Australian Bight. Figure 8 illustrates the pressure tracks and synoptic patterns observed during the storm events.
- The pressure systems converged and intensified over uncharacteristically warmer waters in the Tasman Sea that were 2.5°C above normal temperatures.
- This synoptic pattern remained stationary for several days, allowing south-easterly onshore winds averaging 40 km/h to generate high-energy waves.

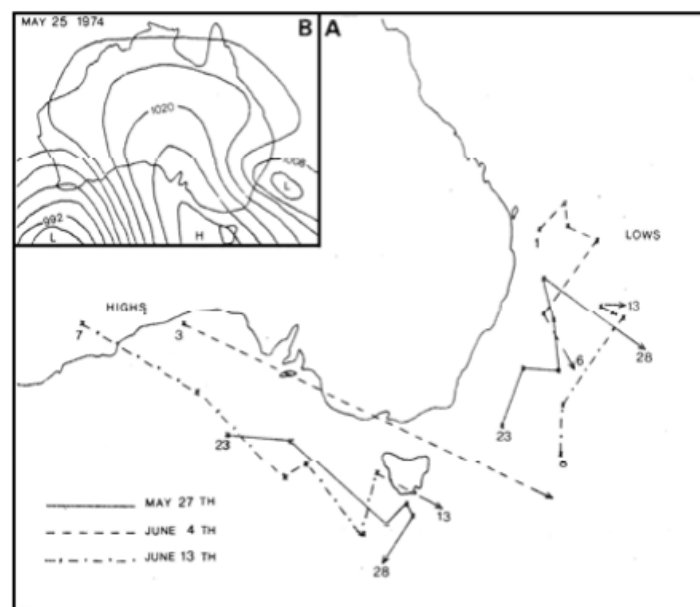


Figure 8: a) Pressure tracks and b) Synoptic Chart from 1974 anomalous storm event (Bryant and Kidd 1975).

The waves' erosive effect was further exacerbated by unusually high tides occurring at the same time. The high tides were the result of proxigean spring tides (syzygy and perigee), which occur when the moon is closest to the Earth on its elliptical orbit, whilst at the same

time aligning itself between the Earth and the Sun. The gravitational forces cause the Earth's tidal range to heighten.

The storm effects had an increased impact on the resulting character of the beaches because they occurred within such a short time frame and therefore did not allow time for the beach to recover between events. As a result their effects were additive. Jeans and Davies (1984) inferred that this erosion event was clearly exceptional, and likely to have a recurrence interval of about 100 years. Bryant and Kidd concluded that all beaches along the NSW coast were affected by the 1974 storms, though well defined trends were highlighted in relation to greatest erosion. Erosion was most substantial at;

- pocket beaches;
- beaches where wave energy was concentrated by refraction;
- where seawalls had been constructed; and
- adjacent to inlet mouths.

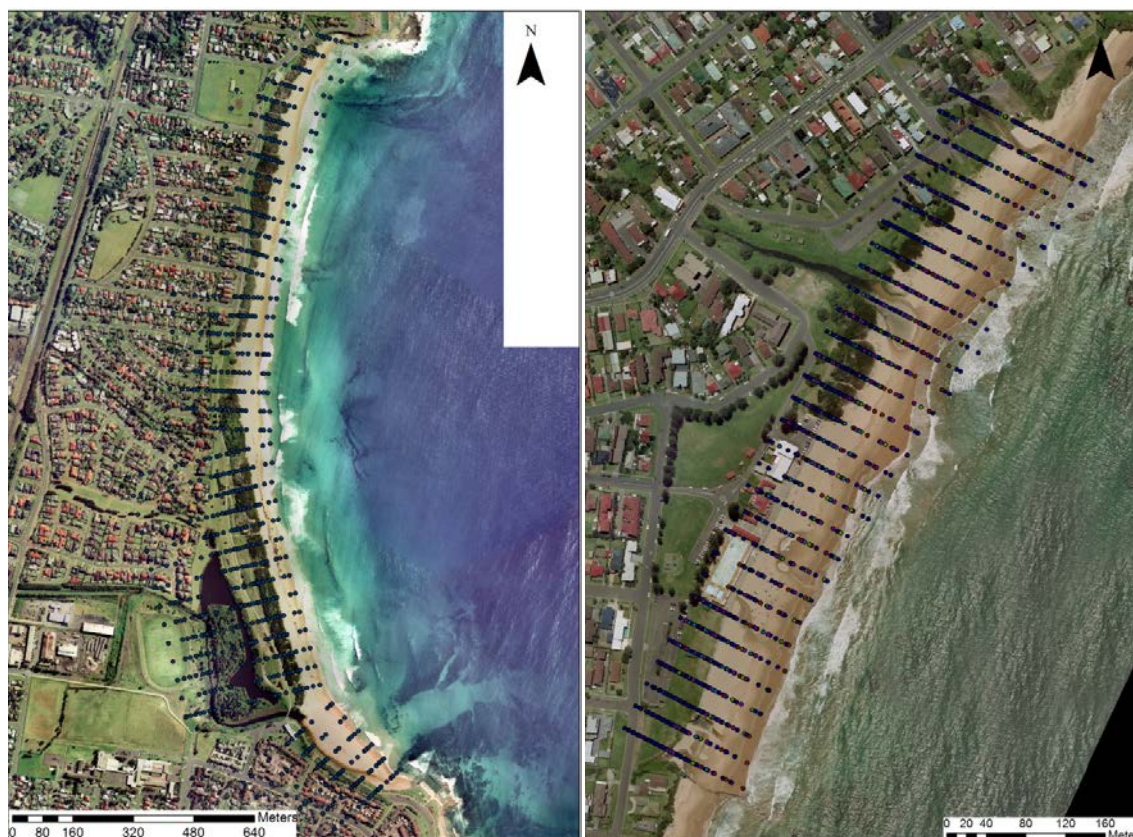
Rollason (2011) provides a brief summary of the environmental factors within the study area:

*“Wollongong’s beaches are typically high energy sandy beaches with occasional rocky shorelines. Wollongong has in places steep and rugged cliffs and bluffs, creating small pocket beaches. In the far northern part of the LGA, cliffs and bluffs dominate the coastline, as the Illawarra escarpment trends eastwards to meet the coast.”*

It is paramount to consider the environmental factors, physical forces, and existing beach morphologies as outlined in this chapter as they allow for an informed discussion of the changes detected within the whole system. The following chapter will outline how the changes at Woonona/Bellambi and Thirroul beaches were detected.

## 4.0 Methodology

The aim of this report is to improve the councils' knowledge base for Wollongong beaches as well as the understanding of dune change detection techniques for the coast. Woonona/Bellambi Beach and Thirroul Beach (Figure 9) were used as case studies. A review of the previously completed reports into the coastal zone was conducted so that it was possible to highlight potential areas in need of further research. Consideration was given to availability of data as this would allow construction of a realistic scope for this project. The compiled data allowed for a range of change detection techniques to be applied to the selected beaches using geographic information system (GIS) analysis.



**Figure 9: a) Woonona/Bellambi Beach and b) Thirroul Beach showing the photogrammetric data points.** The available data is summarised in Table 4 and included a) raw photogrammetric data spanning irregular intervals between 1955 and 2007, b) aerial photographs spanning 1938 to 2011, and c) LiDAR data covering the Wollongong LGA. The photogrammetric data points and blocks are numbered from south to north and are illustrated in Appendix B and C. The change detection encompassed similar techniques used and compared in Hanslow (2007) for McMasters Beach. The three techniques to monitor beach change at Woonona/Bellambi Beach and Thirroul Beach were 1) dune volume calculation, 2) 2 m AHD contour movement analysis, and 3) vegetation line tracking. Observations were also collected post storm events

that occurred throughout the collation of this report from beaches between City Beach and Austinmer Beach.

**Table 4: Available Photogrammetric Data and Aerial Photography**

| Dates | Photogrammetric Data |          | Aerial Photographs |          |
|-------|----------------------|----------|--------------------|----------|
|       | Woonona/Bellambi     | Thirroul | Woonona/Bellambi   | Thirroul |
| 1938  |                      |          |                    |          |
| 1951  |                      |          |                    |          |
| 1955  |                      |          |                    |          |
| 1961  |                      |          |                    |          |
| 1964  |                      |          |                    |          |
| 1972  |                      |          |                    |          |
| 1974  |                      |          |                    |          |
| 1976  |                      |          |                    |          |
| 1981  |                      |          |                    |          |
| 1982  |                      |          |                    |          |
| 1987  |                      |          |                    |          |
| 1990  |                      |          |                    |          |
| 1993  |                      |          |                    |          |
| 1994  |                      |          |                    |          |
| 1999  |                      |          |                    |          |
| 2000  |                      |          |                    |          |
| 2001  |                      |          |                    |          |
| 2002  |                      |          |                    |          |
| 2006  |                      |          |                    |          |
| 2007  |                      |          |                    |          |

## 4.1 Method One – Dune Volume

Changes in dune volume were detected through comparison between profiles surveyed using photogrammetric data provided by OEH (Appendix D and E). This enabled long term volume change analysis undertaken at consistent profiles across the sub aerial beach systems. Profile locations were kept constant at each beach.

Photogrammetric data was available for Woonona/Bellambi beach for time slices within 1955 to 2007, while Thirroul had less available data from between only 1961 to 2007. The volume was calculated by using a numerical integration method known as the trapezoidal rule that approximates the area under the profile curve (dune profile). The method calculates the area of the trapezium formed for each subinterval- i.e. between each photogrammetric point. The sum of these trapeziums provides the total area under the curve:

$$\text{Area} = \sum (\text{average height between two adjacent points within profile}) \times (\text{width})$$

selected separately for each profile (Figure 10). The baseline was selected for each individual profile by using a georeferenced image of the beaches to measure the distance from 0 AHD to the back of the eroding dune face. Visual inspection of the Cardno (2010) photogrammetric profiles was also conducted to help define the back of the eroding dune face. Choosing a specific baseline for each profile removed the inclusion of anthropogenic development (i.e. bike baths and roads) landwards of the active dune, as well as minimising the effects of vegetation cover. Both factors hinder the accuracy of the profiles to model the dune topography. The area calculated included all sediment bounded by:

- a vertical baseline behind the active dune face;
- the surface of the dune inferred by the photogrammetric points; and
- a horizontal line at 0 m AHD.

This area was assumed to apply to a 1 m slice of dune due to the 0.5 m planimetric accuracy of the photogrammetric data. Figure 10 (below) illustrates the area calculated as dune volume. The term ‘dune’ is used throughout this report, however, it also includes beach sediment within this bound.

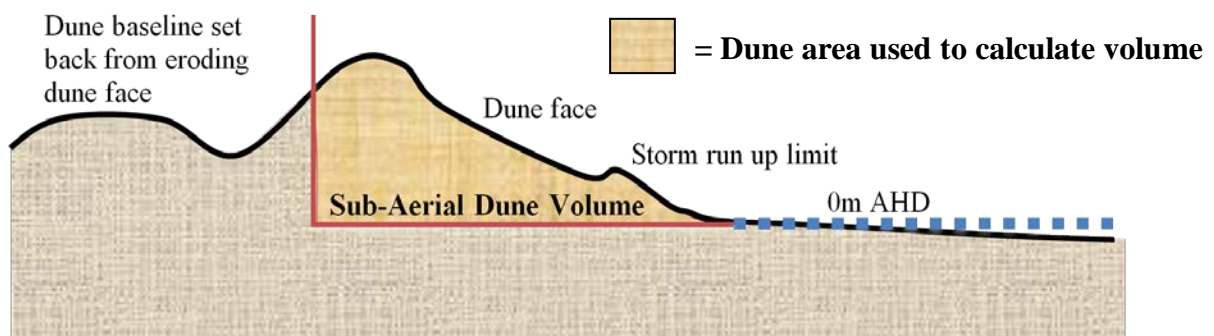


Figure 10: The area considered dune volume for within each profile.

#### 4.1.1 LiDAR

LiDAR was also available and was analysed similar to the photogrammetric data. The LiDAR data set is conglomeration of various sets of 2005-2007 data. The profile positions of the photogrammetric data were used to georeferenced the LiDAR layer to ensure the LiDAR volumes were calculated from the same profile locations. Profiles were extracted from the LiDAR data and volumes were able to be compared to the photogrammetric data volumes.

## **4.2 Method Two –2 m AHD Contour Tracking**

A proxy scarp location was approximated across Woonona/Bellambi and Thirroul beaches. A relative contour level of 2 m was chosen as it has been considered to reflect the approximate midpoint of the active dune face (Figure 10) or scarp. This technique was used by Hanslow (2007) due to the advantage of minimising the effects of varying dune levels and slumping caused by rare events such as storms.

The 2 m contour line was compared for all available years at both beaches so that sequential movement of the dune face could be interpreted. The contour was created using the photogrammetric data and was therefore restricted to the time periods of available data and the resolution of the photogrammetric data. The contours were created using triangular irregular networks (TIN) to approximate the topography between data points. A TIN is constructed by triangulating a set of data points to form a network of triangles. This method satisfies the Delaunay triangle criterion, which states that no vertex should lie within the interior of any of the circumcircles of the triangles in the network.

The amount of movement of the 2 m contour was calculated using ArcMap to measure a series of distances between consecutive data sets of photogrammetric data. An average of these measurements was taken for each block. The shift in the 2 m contour line was tabulated for both beaches. The shifts were categorised as either; landwards (accretionary), seawards (receding), or stable (no considerable shift in position).

## **4.3 Method Three – Vegetation Line Movement**

The vegetation line is defined as the boundary between the landward natural vegetation assemblage and the unvegetated beach zone (Fenster and Hayden, 2007). All available orthorectified aerial photographs were digitised and georeferenced to allow relative comparison of the vegetation line. The position of the vegetation line was highlighted and compared between years for Woonona/Bellambi and Thirroul beaches. The photograph time spans varied per beach, Woonona/Bellambi- 1936—2011, while Thirroul had available 1955—2011.

Aerial photographs were georeferenced using a technique called rubber sheeting. This process involved identifying a series of ground control points and warping the aerial photograph to match the points using a second-order polynomial transformation. This method optimizes local accuracy between photos. Road intersections, stream intersections, bridges,

and sports fields were used for control points as they are considered stationary, real world points. A minimum of fifteen control points were used to ensure a RMSE (root mean square error) below 5 m. RMSE is the measure of difference between locations that are known and locations that have been interpolated or digitized.

#### **4.4 Monitoring Anomalous Storm Events**

Two large storm events occurred throughout the year of this reports research. It is important that such storm events are monitored in a way that informs management and allows for proactive management for similar storm events in the future. Observations were taken along a large portion of the Wollongong LGA coastline, between City Beach and Austinmer Beach. The first event occurred on the 8<sup>th</sup> of March, involving south-easterly swells up to 4 m as well as storms with winds of up to 85 km/h.

The second event occurred on the 5<sup>th</sup> of June and was more dramatic than the March event. BoM issued warnings of severe weather conditions during the East Coast Low including heavy surf and winds moving south-south-west that were particularly threatening for south facing beaches. A combination of strong winds up to 102 km/hr, the low pressure system, and spring tides produced near record high water levels along the study area. Low-lying areas and coastal creeks and rivers experienced flooding. Many beaches within the study area have a southern aspect and were therefore most vulnerable to the northward directed swells. Further observations were taken at beaches between South Beach and Austinmer, with photographs taken at selected beaches.

## 5.0 Results

### 5.1 Dune Volume

The calculated volumes of dune sediment display a large amount of variability at the two beaches investigated. The following subchapters display the volumes at each profile for each block and beach (Figures 11—15; Tables 5—9). The changes at each block of data between consecutive years is summarised in point form to allow ease of interpretation of accretion-erosion periods. Possible reasons for these changes are discussed in Chapter 7. Refer to Appendix B and C for block locations.

#### 5.1.1 Woonona/Bellambi:

##### Block 1:

Profiles at Block One experienced trends of net accretion evenly spread across the profiles since 1961. The dunes appear to stabilise out from 1987 onwards and begin to fluctuate at the 200 to 250 m<sup>3</sup> level until the final data set (2007).

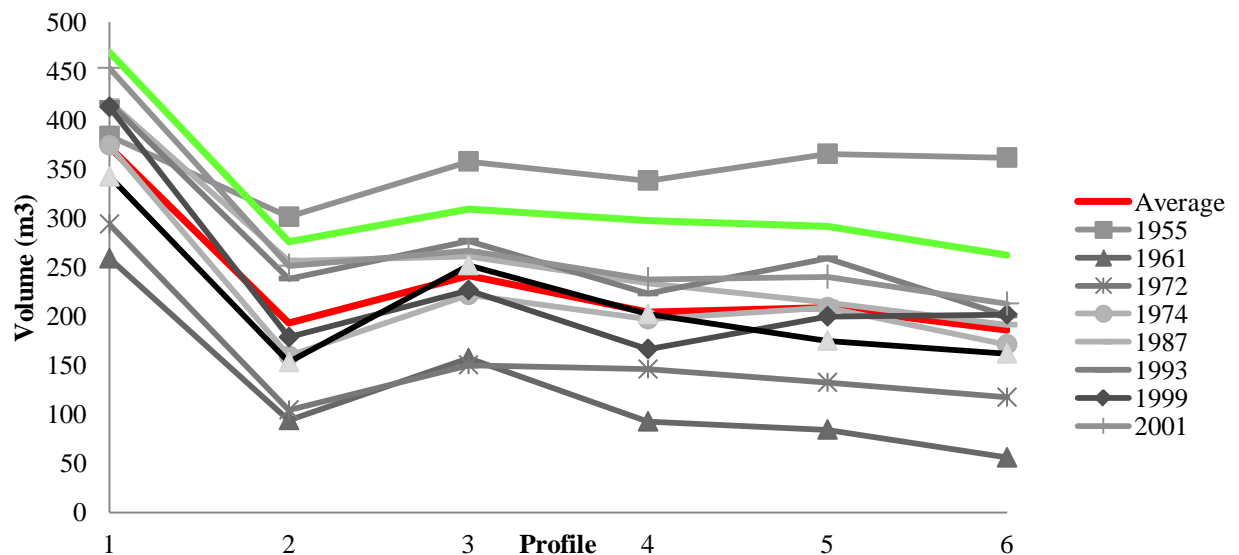


Figure 11: Dune volumes calculated from available photogrammetric data between 1955 and 2007 for Block One.

Table 5: Summary of dune volume change at Block 1, Woonona/Bellambi.

| Year      | Summary   |
|-----------|---|
| 1955      | Largest dune volumes.                                       |
| 1961      | Lowest dune volumes.  |
| 1961-1972 | Slight increase in dune volumes.                            |
| 1972-1974 | Moderate increase in dune volume, despite 1974 storm.       |
| 1974-1987 | Moderate increase in dune volume particularly at Profile 2. |
| 1987-1993 | Small increase in all dune volumes apart from Profile 2.    |
| 1993-1999 | Small decrease in dune volumes.                             |
| 1999-2001 | Small increase in dune volumes.                             |
| 2001-2007 | Small decrease in dune volumes                              |
| LIDAR     | Similar dune volumes as 2001, however, slightly higher.     |



## Block 2:

Block 2 accretes in volume from 1961 to 1974, at which point the dune volumes decreased. 1974 onwards the dune volumes experienced high accretion until 1993. Dune volumes dropped in 1999 then rebuild to fluctuate through to 2007

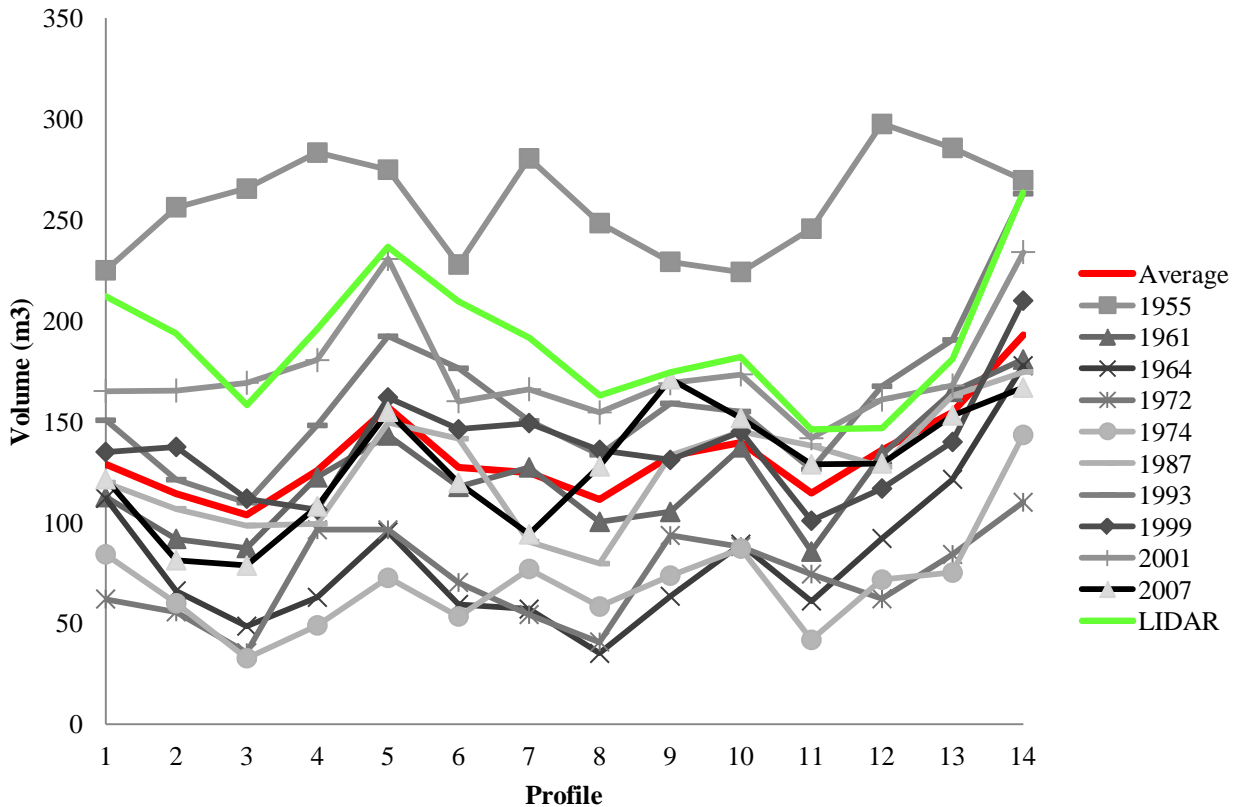


Figure 12: Dune volumes calculated from available photogrammetric data between 1955 and 2007 for Block Two.

Table 6: Summary of dune volume change at Block 2, Woonona/Bellambi.

| Year      | Summary  |
|-----------|--|
| 1955      | Largest dune volumes.  |
| 1961      | Dune volume near average of all years.   |
| 1961-1964 | Moderate increase across all profiles.   |
| 1964-1972 | Dunes volumes remain at similar levels with generally small decreases across all profiles apart from Profile 4 and 9 which experience minor accretion. |
| 1972-1974 | Dune volumes decreased across most profiles by a small amount, while the remaining fluctuated above 1972 by a small amount.                            |
| 1974-1987 | Large period of accretion at all profiles.   |
| 1987-1993 | Continued accretion at all profiles.   |
| 1993-1999 | Small decrease in dune volumes at all profiles apart from Profile 2.   |
| 1999-2001 | Moderate period of accretion at all profiles   |
| 2001-2007 | Moderate level of recession in profiles to the south, whilst profiles northwards of Profile 8 only experience low levels of recession.                 |
| LIDAR     | Very similar volumes to 2001 levels represented by the photogrammetric data.   |

### Block 3:

Block 3 appears to accrete from 1961 until 1972. The dune profiles experience a decrease in volume in 1974. The dunes have a large amount of accretion up to the 1993 period. They then appear to stabilise out with only small fluctuations, until a large accretion period in 2007.

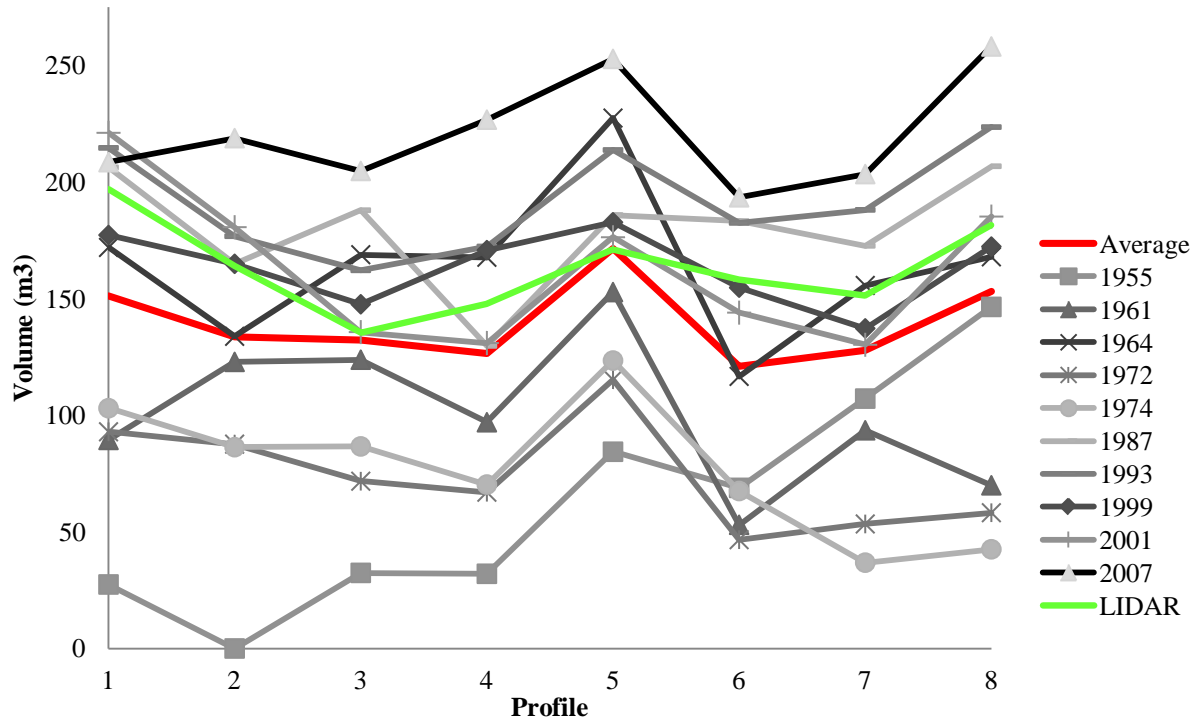


Figure 13: Dune volumes calculated from available photogrammetric data between 1955 and 2007 for Block Three.

Table 7: Summary of dune volume change at Block 3, Woonona/Bellambi.

| Year      | Summary   |
|-----------|---|
| 1955      | Very low dune volumes in profiles at the southern portion of the block. |
| 1955-1961 | Moderate levels of accretion spread evenly across profiles 1 to 5.      |
| 1961-1964 | Moderate levels of accretion spread evenly across all profiles.         |
| 1964-1972 | High levels of dune recession spread evenly across all profile.         |
| 1972-1974 | Dune levels did not largely change from the low levels of 1972.         |
| 1974-1987 | Very large levels of accretion at all profiles.                         |
| 1987-1993 | Dune volumes experience slight accretion at most profiles.              |
| 1993-1999 | Small levels of recession at northern profiles.                         |
| 1999-2001 | Dune volumes experience a low amount of recession at most profiles.     |
| 2001-2007 | Dune volumes experience large accretion.                                |
| LIDAR     | Dune volumes appear similar to that of 2001.                            |

#### Block 4:

Block 4 volumes experience small fluctuations until 1987, at which point there are large dune volume increases. Volumes continue to fluctuate around this new high volume level until 1999 – 2001 at which time the dunes appear to be considerably stripped of sediment. The dunes then increase in volume again to their highest levels in 2007.

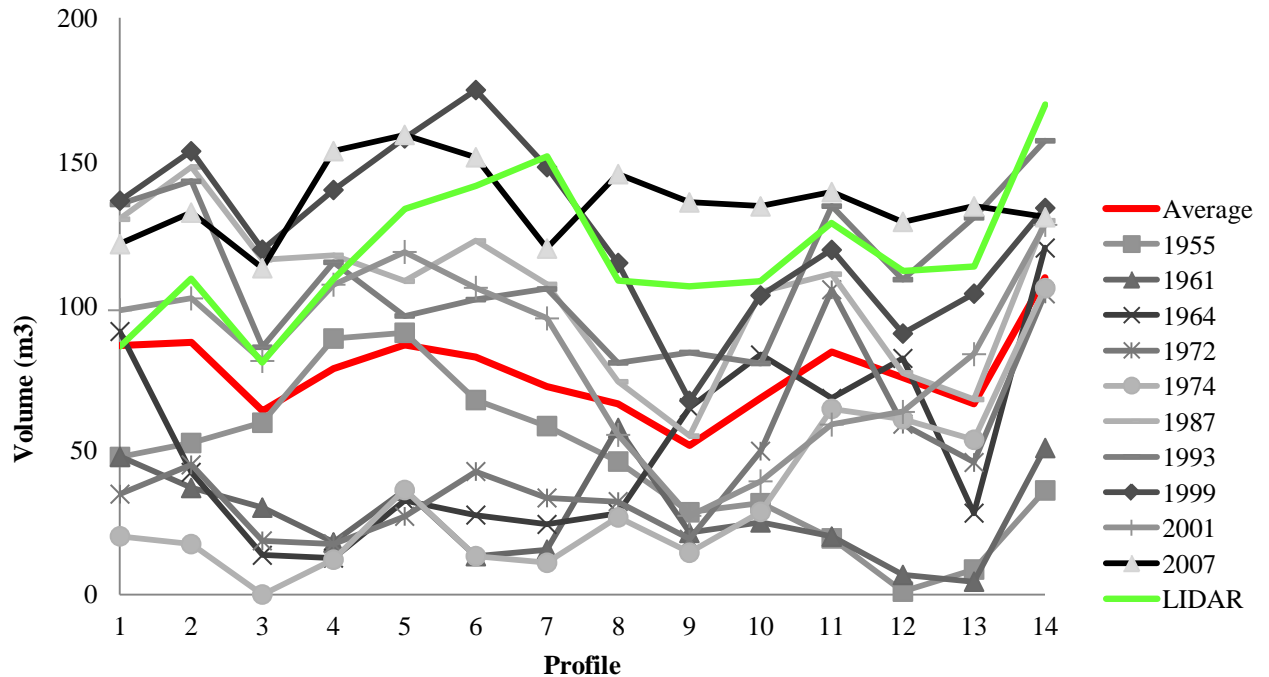


Figure 14: Dune volumes calculated from available photogrammetric data between 1955 and 2007 for Block Four.

Table 8: Summary of dune volume change at Block 4, Woonona/Bellambi.

| Year      | Summary   |
|-----------|---|
| 1955      | Very low dune volumes in northern profiles, southern profiles are close to the time series average.   |
| 1955-1961 | Very low dune volumes with considerable decreases in the southern portion.  |
| 1961-1964 | Considerable increase in dune volume in northern profiles. Southern profiles are relatively stable.   |
| 1964-1972 | High levels of dune recession spread evenly across all profile.   |
| 1972-1974 | Small decreases in volume in most profiles.   |
| 1974-1987 | Large increases in all dune volumes, particularly in southern profiles.   |
| 1987-1993 | Small fluctuations across profiles.   |
| 1993-1999 | Significant dune volume increases in profiles 3 to 8. Small fluctuations across all the other profiles.   |
| 1999-2001 | Moderate decrease in all dune volumes.  |
| 2001-2007 | Large increases in dune volume across all dune volumes.   |
| LIDAR     | Levels higher than average, slightly less than 2007. They are similar to the southern profiles of 2001 data, but do not match up consistently across the whole block. |

### 5.1.2 Thirroul:

The Thirroul sand dunes appear to fluctuate early on, before a very large decrease in 1974 due to the storm event. They then rebuild and fluctuate about a high level from 1993, onwards.

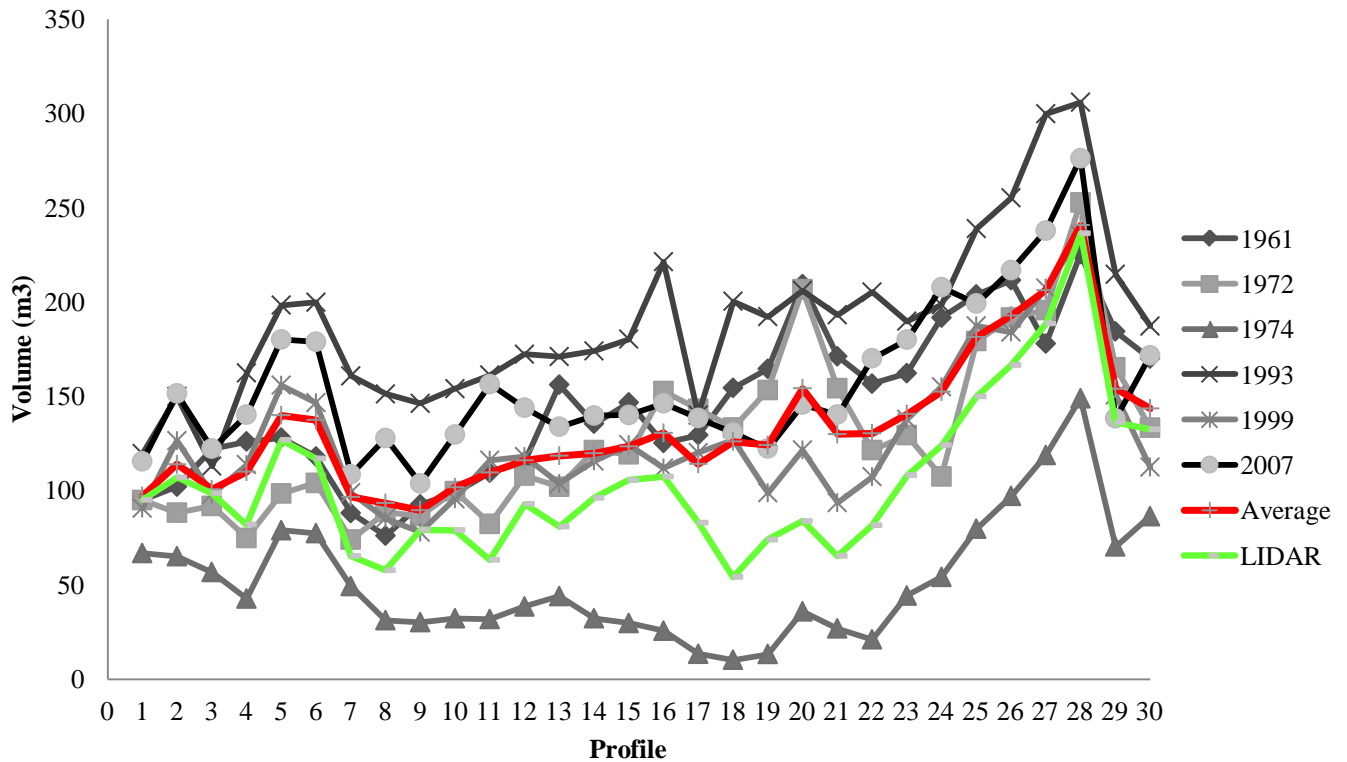


Figure 15: Dune volumes calculated from available photogrammetric data between 1955 and 2007 for Thirroul Beach.

Table 9: Summary of dune volume change at Thirroul.

| Year      | Summary   |
|-----------|---|
| 1961      | Dune volumes are close to time series average, higher within the northern portion of the beach. |
| 1961-1972 | Dunes fluctuate about the 1961 levels, but are generally lower.                                 |
| 1964-1972 | High levels of dune recession spread evenly across all profile.                                 |
| 1972-1974 | Dune volumes experience very considerable decreases, reflecting the 1974 storm event.           |
| 1974-1993 | Dune volumes build back up very considerably to their highest levels.                           |
| 1993-1999 | Moderate decrease in all profiles.  |
| 1999-2007 | Dune volumes increase at all profiles.  |
| LIDAR     | Relatively low dune volumes, similar to those of the 1999 photogrammetric profile.              |

### 5.1.3 Total Historical Dune Volume Change

The dune volumes were totalled separately for Woonona/Bellambi and Thirroul for all available time slices (Table 10 and 11 respectively). This allowed for an assessment of the dune volume history and easy evaluation of periods that display net accretion or net erosion. The total beach change was estimated using the approximate length of 2000 m of beach for Woonona/Bellambi, and 1000 m for Thirroul. The following formula was used:

$$\text{Total Beach Volume} = \frac{\text{Volume in Profiles Only}}{\text{Number of Profiles}} \times \text{Beach Length}$$

Calculation of total dune volume change after the 1974 storm events allows for quantitative estimates of the storm cut loss. It is calculated to be an average of ~77 m<sup>3</sup>/m for Thirroul Beach—or a cut of 76,719.8 m<sup>3</sup> for the whole of the system.

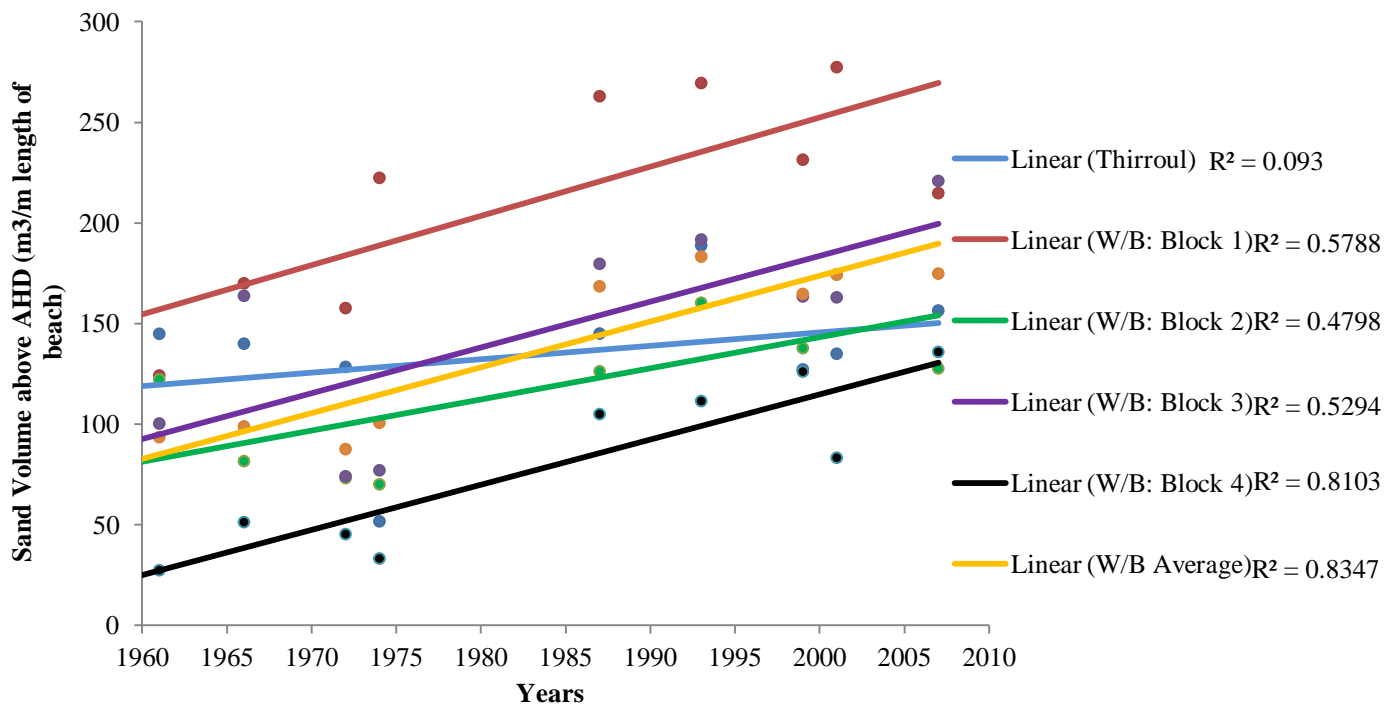
**Table 10: Woonona/Bellambi system total volume (m<sup>3</sup>), differences between each time slice, and the averaged volume change per year.**

| Year | Total Volume<br>in Profiles<br>only (m <sup>3</sup> ) | Difference<br>(m <sup>3</sup> ) | Years<br>Between<br>Surveys | Mean Yearly<br>Volume Change<br>(m <sup>3</sup> /year/profiles) | Total Beach<br>Volume (m <sup>3</sup> ) | Total Beach<br>Change (m <sup>3</sup> ) |
|------|---|---------------------------------|-----------------------------|---|---|---|
| 1955 | 6938.1382   | -                               | -                           | -   | 330387.5                                | -                                       |
| 1961 | 3642.9714   | -3295.1668                      | 6                           | -549.19447  | 173474.8                                | -156913                                 |
| 1966 | 3971.4247   | 328.45328                       | 5                           | +65.690656  | 189115.5                                | +15640.63                               |
| 1972 | 3199.1576   | -772.26709                      | 6                           | - 128.71118   | 152340.8                                | -36774.6                                |
| 1974 | 3397.6909   | 198.53328                       | 2                           | +99.266639  | 161794.8                                | +9453.9                                 |
| 1987 | 6253.1679   | 2855.4771                       | 13                          | +219.65208  | 297769.9                                | +135975.1                               |
| 1993 | 6956.5885   | 703.4206                        | 6                           | +117.23677  | 331266.1                                | +33496.2                                |
| 1999 | 6390.9963   | -565.5922                       | 6                           | -94.265367  | 304333.2                                | -26933                                  |
| 2001 | 6574.6227   | 183.62635                       | 2                           | +91.813176  | 313077.6                                | +8744.1                                 |
| 2007 | 6746.1533   | 171.53066                       | 6                           | +28.588443  | 321245.4                                | +8168.1                                 |

**Table 11: Thirroul system total volume (m<sup>3</sup>), differences between each time slice and the averaged volume change per year.**

| Year | Total Volume in Profiles only (m <sup>3</sup> ) | Difference (m <sup>3</sup> ) | Years Between Surveys | Mean Yearly Volume Change (m <sup>3</sup> /year/all profiles) | Total Beach Volume (m <sup>3</sup> ) | Total Beach Change (m <sup>3</sup> ) |
|------|---|------------------------------|-----------------------|---|--------------------------------------|--------------------------------------|
| 1961 | 4347.2895                                       | -                            | -                     | -   | 144909.6                             | -                                    |
| 1972 | 3853.1639                                       | -494.12551                   | 11                    | -44.920501  | 128438.8                             | -16470.9                             |
| 1974 | 1551.569  | -2301.595                    | 2                     | -1150.7975  | 51718.97                             | -76719.8                             |
| 1993 | 5662.991  | 4111.4221                    | 19                    | +216.39063  | 188766.4                             | +137047.4                            |
| 1999 | 3816.1081                                       | -1846.8829                   | 6                     | -307.81382  | 127203.6                             | -61562.8                             |
| 2007 | 4693.7932                                       | 877.68505                    | 8                     | +109.71063  | 156459.8                             | +29256.2                             |

The coefficient of determination ( $R^2$  values) was calculated based on the changes in ‘profile only’ dune volume at each block of photogrammetric data (Figure 16). The values with a high  $R^2$  value indicate that the modelled line of best fit explains the trends of volume change well. Woonona/Bellambi Block 4 and Woonona/Bellambi Average present somewhat high  $R^2$  values (0.8103 and 0.8347 respectively). Thirroul has a very low  $R^2$  value (0.093) suggesting that the beach has highly variable dune volumes.



**Figure 16: Time series of dune volume change at Thirroul and Woonona/Bellambi (W/B) in m<sup>3</sup> per meter length of shoreline each with a line of best fit overlaid.  $R^2$  values are displayed for each beach/block.**



## 5.2 2 m Contour Tracking

Tracking of the 2 m contour allowed for characterisation of the seawards, landwards, or negligible change in the active dune face position. The movement occurring is outlined below and shown in Figures 17 to 21 for Woonona/Bellambi and Figure 22 for Thirroul. The TIN was created using all available photogrammetric data points across the available years of data. Areas between points are interpolated by the TIN. The black line in the TIN output represents the area that lies between 1.9 and 2.1 m. The movement of the 2 m contour occurring through the study period at each beach is summarised in tables 12 to 14.

### 5.2.1 Woonona/Bellambi

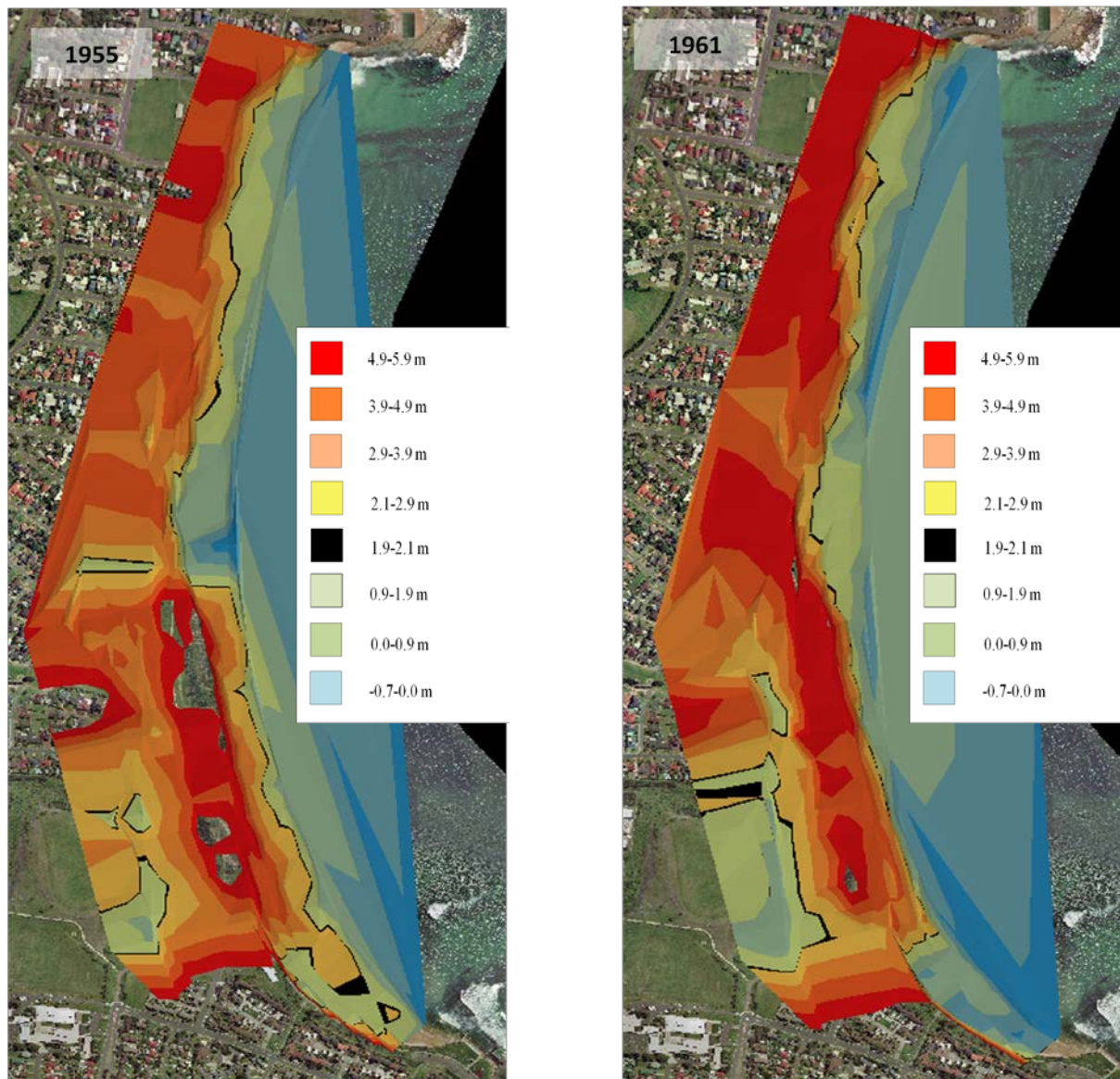


Figure 17: Tracking of the 2 m contour across Woonona and Bellambi beach between 1955 and 1961. The 2 m contour is shown by the bold black line.

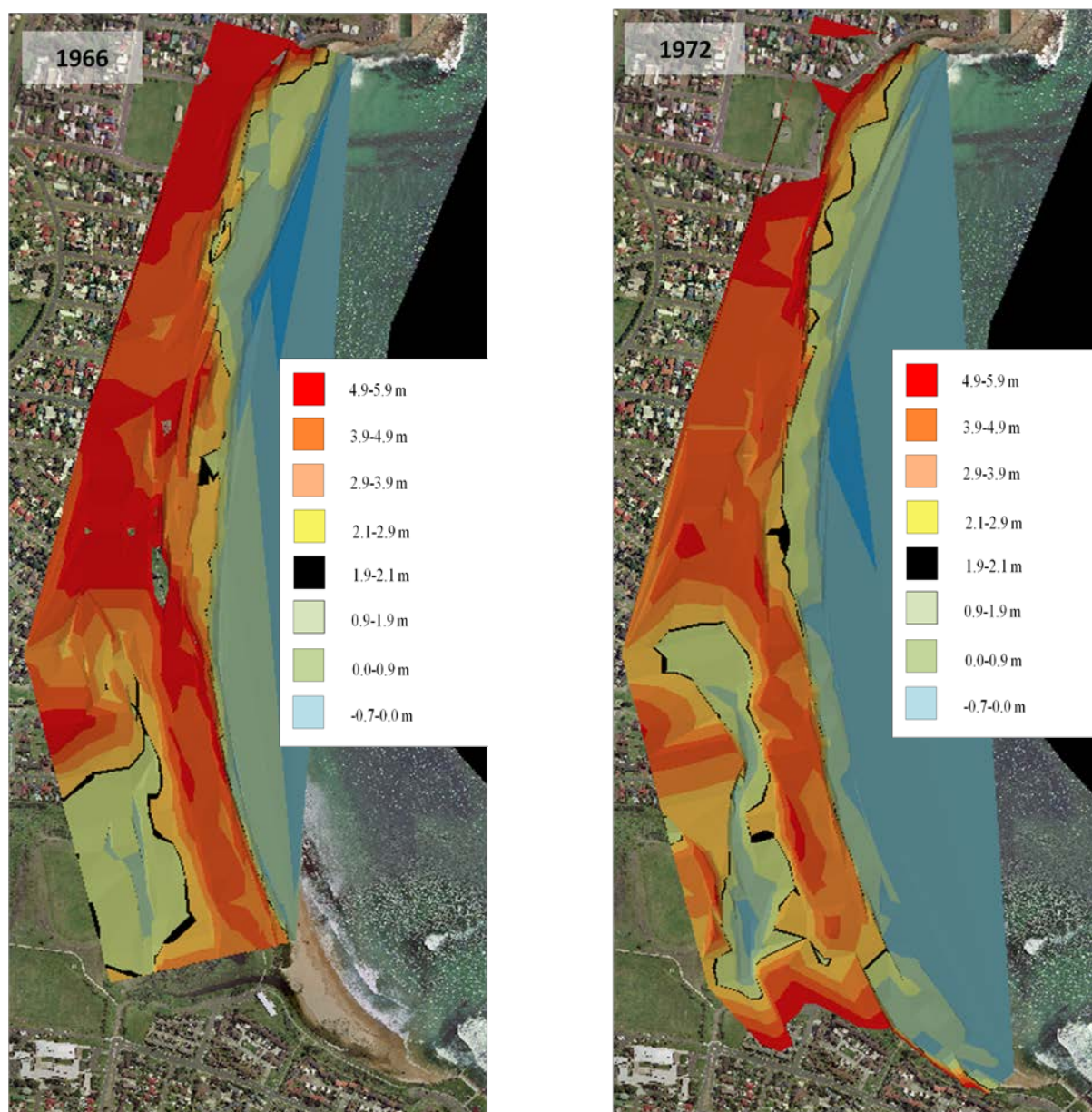


Figure 18: Tracking of the 2 m contour across Woonona and Bellambi beach between 1966 and 1972. The 2 m contour is shown by the bold black line.



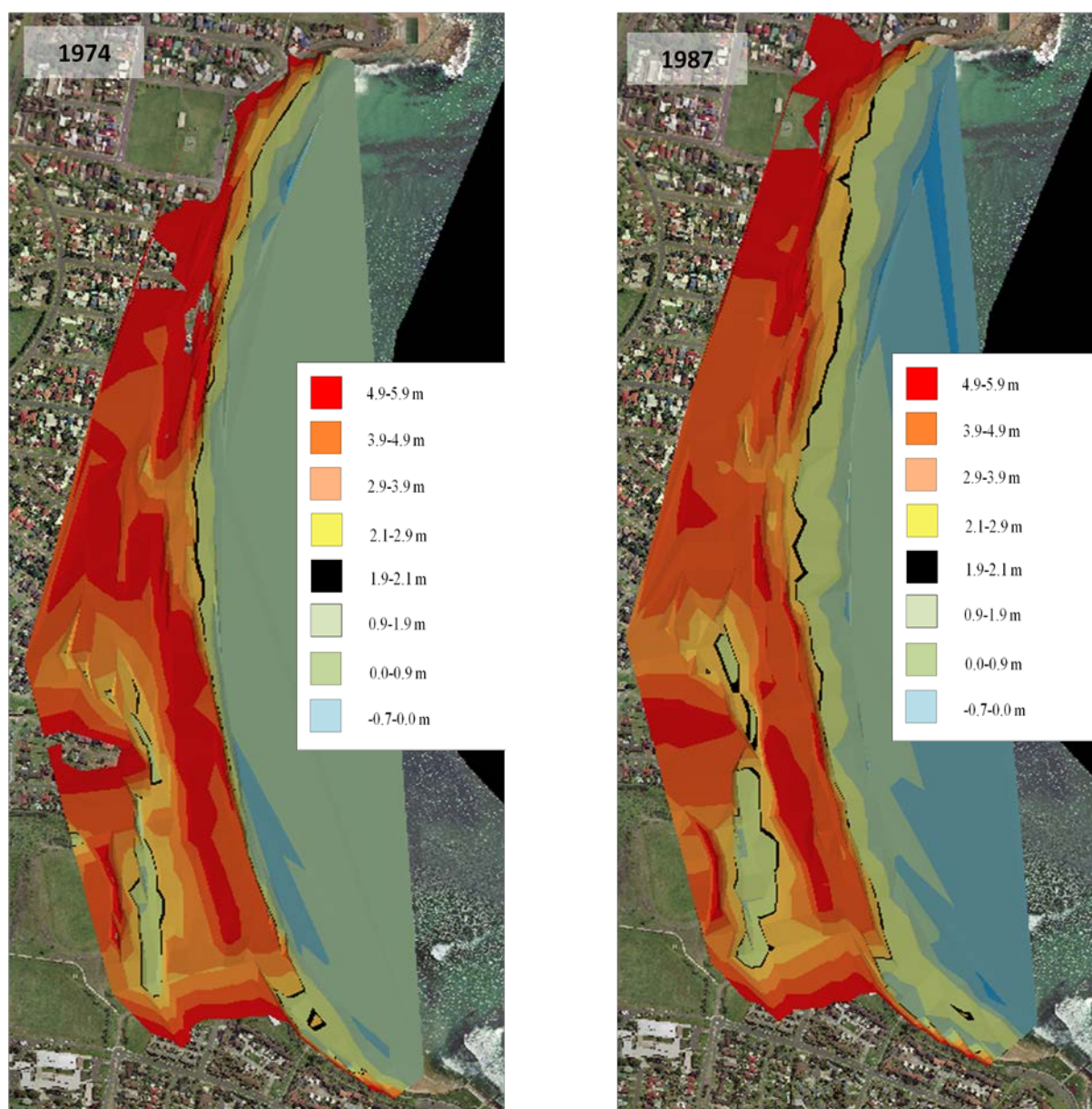


Figure 19: Tracking of the 2 m contour across Woonona and Bellambi beach between 1974 and 1987. The 2 m contour is shown by the bold black line.

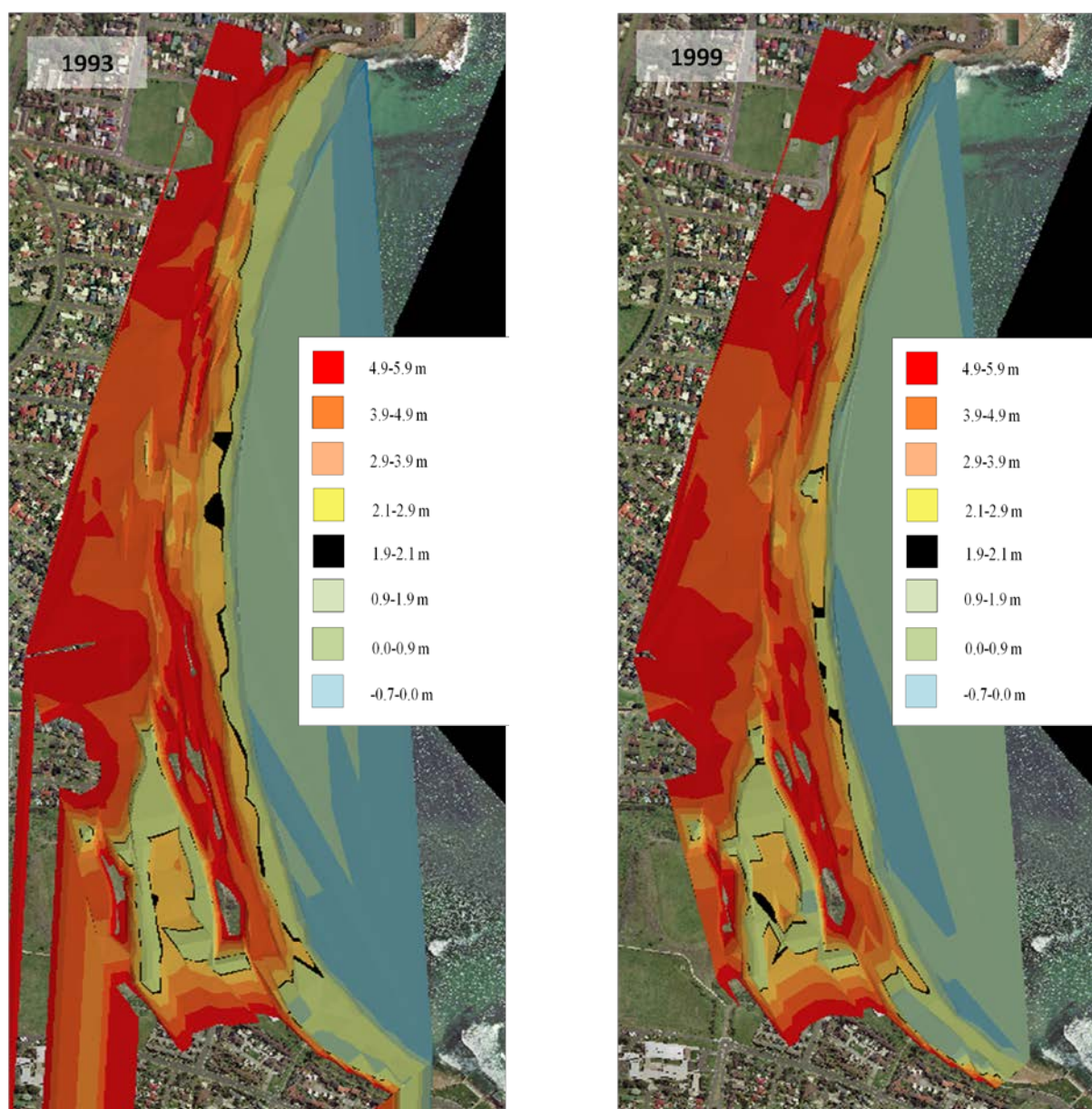


Figure 20: Tracking of the 2 m contour across Woonona and Bellambi beach between 1993 and 1999. The 2 m contour is shown by the bold black line.



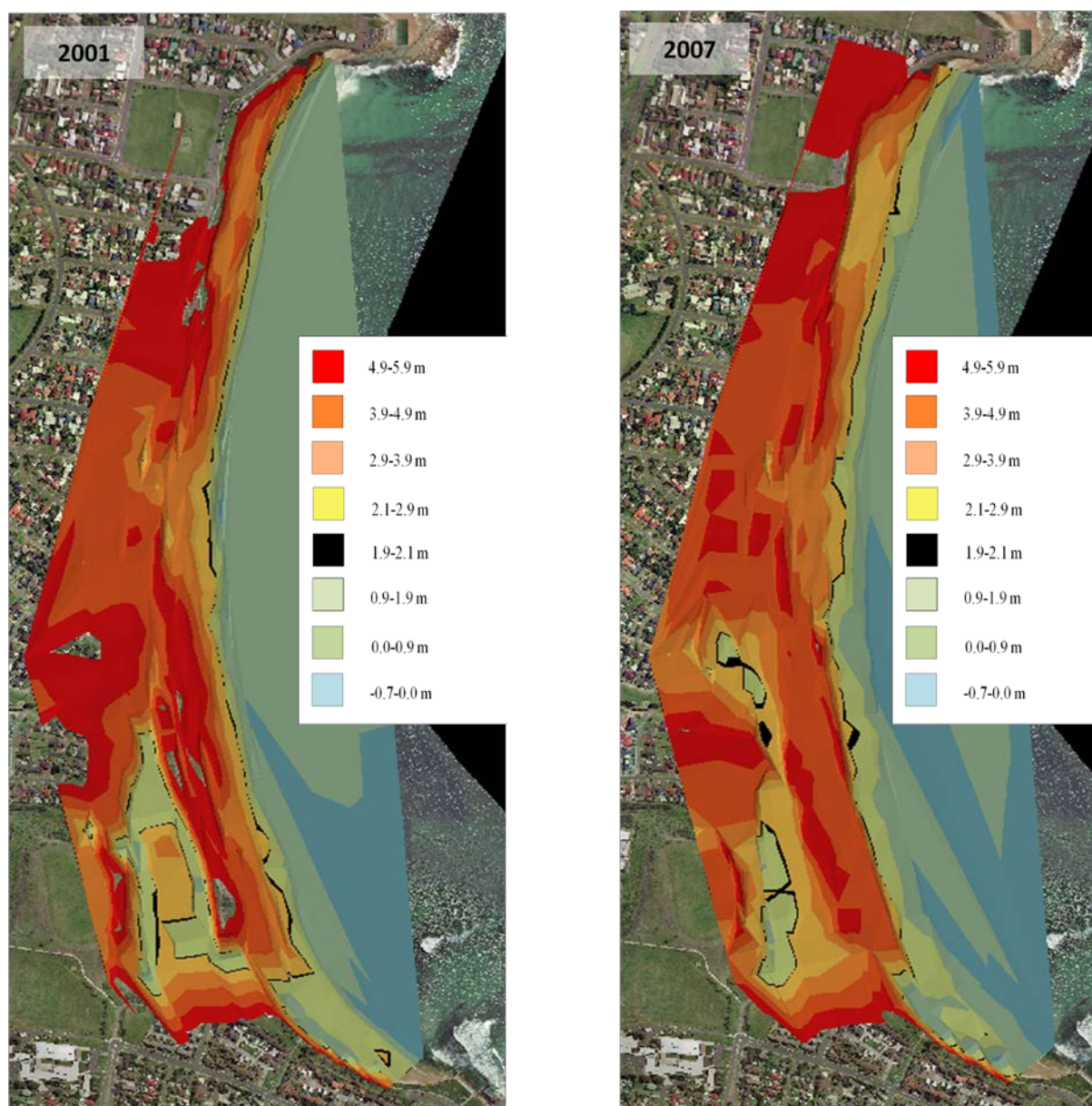


Figure 21: Tracking of the 2 m contour across Woonona and Bellambi beach between 2001 and 2007. The 2 m contour is shown by the bold black line.

### 5.2.2 Block One

Block one: There was no detectable change in the 2 m contour at Block One of Woonona/Bellambi beach.

### 5.2.3 Block Two

The changes occurring at Block Two have been summarised in Table 5.

**Table 12: Change occurring at photogrammetric Block Two (Bellambi Beach) in the 2 m contour.**

| Year        | 2m Contour Movement | Description   | Avg. 2 m AHD Contour Shift (m) |
|-------------|---------------------|---|--------------------------------|
| 1955 - 1961 | Landward            | The 2m contour has receded at a generally consistent distance of 37m.   | -37                            |
| 1961 - 1966 | Landward            | A landward recession of only 5m in the north section of the block, whilst the southern half receded 27m   | -5 to -27                      |
| 1966 -1972  | Stable              | No detectable movement.   | 0                              |
| 1972 -1974  | Stable              | No detectable movement.   | 0                              |
| 1974 - 1987 | Stable              | No detectable movement.   | 0                              |
| 1987 - 1993 | Seaward             | Movement seawards most noticeable in the centre of the block, approximately 20-25m, whilst a positive change of only about 5m occurred at northern and southern block portions. | 5 to 20-25                     |
| 1993 - 1999 | Landward            | A small recession occurred at the northern portion of the beach of approximately 20m.   | 0 to -20                       |
| 1999 - 2001 | Seaward             | The 2m contour has accreted at a generally consistent distance of 12m.  | 12                             |
| 2001 - 2007 | Landward            | A small recession occurred, most noticeably in the southern half of approximately 27m, while the northern half receded approximately 8m.  | -8 to -27                      |

### 5.2.4 Block Three

The changes occurring at Block Three have been summarised in Table 6.

**Table 13: Change occurring at photogrammetric Block Three (Woonona Beach) in the 2 m contour.**

| Year        | 2m Contour Movement | Description   | Avg. 2 m AHD Contour Shift (m) |
|-------------|---------------------|---|--------------------------------|
| 1955 - 1961 | Seaward             | The northern end did not shift, while the southern end accreted at an average of 18m                | 0 to 18                        |
| 1961 - 1966 | Seaward             | The 2m contour line accreted at a consistent distance of approximately 40m.                         | 40                             |
| 1966 -1972  | Landward            | The 2m contour line experienced a moderate recession at a consistent distance of approximately 49m. | -49                            |
| 1972 -1974  | Seaward             | A small accretion of approximately 15m.   | 15                             |
| 1974 - 1987 | Seaward             | A small accretion of approximately 18m.   | 18                             |
| 1987 - 1993 | Seaward             | A moderate and consistent accretion of approximately 33m.   | 33                             |
| 1993 - 1999 | Stable              | No detectible movement  | 0                              |
| 1999 - 2001 | Landward            | A small recession of approximately 12m.   | -12                            |
| 2001 - 2007 | Seaward             | A small accretion of approximately 16m. Zero movement in the centre of the block.                   | 0 to 16                        |

### 5.2.5 Block Four

The changes occurring at Block Four have been summarised in Table 7.

**Table 14: Change occurring at photogrammetric Block Four (Woonona Beach) in the 2 m contour.**

| Year        | 2m Contour Movement | Description  | Avg. 2 m AHD Contour Shift (m) |
|-------------|---------------------|--|--------------------------------|
| 1955 - 1961 | Stable              | The 2m contour accreted in some areas, while it recedes in others. Net movement is considered negligible.  | 0                              |
| 1961 - 1966 | Landward            | Most areas experience no detectible change in the northern half of the block, while the southern half receded approximately 22m.   | 0 to -22                       |
| 1966 -1972  | Seaward             | The northern and southern extent of the block did not experience any noticeable change, whilst the centre of the block accreted approximately 34m                                      | 34                             |
| 1972 -1974  | Stable              | The 2m contour accreted in some areas, while it recedes in others. Net movement is considered negligible.  | 0                              |
| 1974 - 1987 | Seaward             | The northern half of the block did not experience any noticeable movement, whilst the southern half moved seawards approximately 34m.  | 34                             |
| 1987 - 1993 | Stable              | The 2m contour accreted in some areas, while it receded in others. Net movement is considered negligible. It is noted that the northern portion of the block accreted a consistent 7m. | 0 to 7                         |
| 1993 - 1999 | Seaward             | The beach experienced moderate accretion, particularly in the central section, of approximately 35m.   | 35                             |

|             |          |  |     |
|-------------|----------|--|-----|
| 1999 - 2001 | Landward | The beach experienced moderate recession consistently across the beach of approximately 26m. | -26 |
| 2001 - 2007 | Seaward  | The beach experienced a small accretion consistently across the beach of approximately 16m.  | 16  |

### 5.2.6 Thirroul

Similar to Woonona/Bellambi Beach, the photogrammetric data was processed using a TIN to describe the 2 m contour as a proxy for the active scarp or dune face. The variability of the 2 m AHD contour is displayed for each year in Figure 22 below.

The changes occurring at Thirroul Beach have been summarised in Table 15.

**Table 15: Change occurring at Thirroul photogrammetric block in the 2 m contour.**

| Year        | 2m Contour Movement | Description  | Avg. 2 m AHD Contour Shift (m) |
|-------------|---------------------|--|--------------------------------|
| 1961 - 1972 | Landward            | A consistent landwards recession, approximately 12m, of the 2 m contour location consistently across the beach.  | -12                            |
| 1972 - 1974 | Landward            | Large landward recession of the 2m contour of approximately 35m in the northern half, and 23 in the centre, decreasing to a shift on only 7m in the southern half. | -7 to -35                      |
| 1974 -1993  | Seaward             | Large seaward movement of the 2 m contour line, more extensive in the north (approximately 60 m) compared to the south (approximately 38 m)                        | 38 to 60                       |
| 1993 - 1999 | Landward            | A moderate recession of the 2 m contour line of approximately 30 m in the north, 20 m in the centre of the beach, and 25 m on the southern end.                    | -20 to -30                     |
| 1999 -2007  | Seaward             | The 2 m contour has accreted at approximately 11 m in the north, and 10 m in the south. The centre of the beach appears to have remained stable.                   | 10 to 11                       |



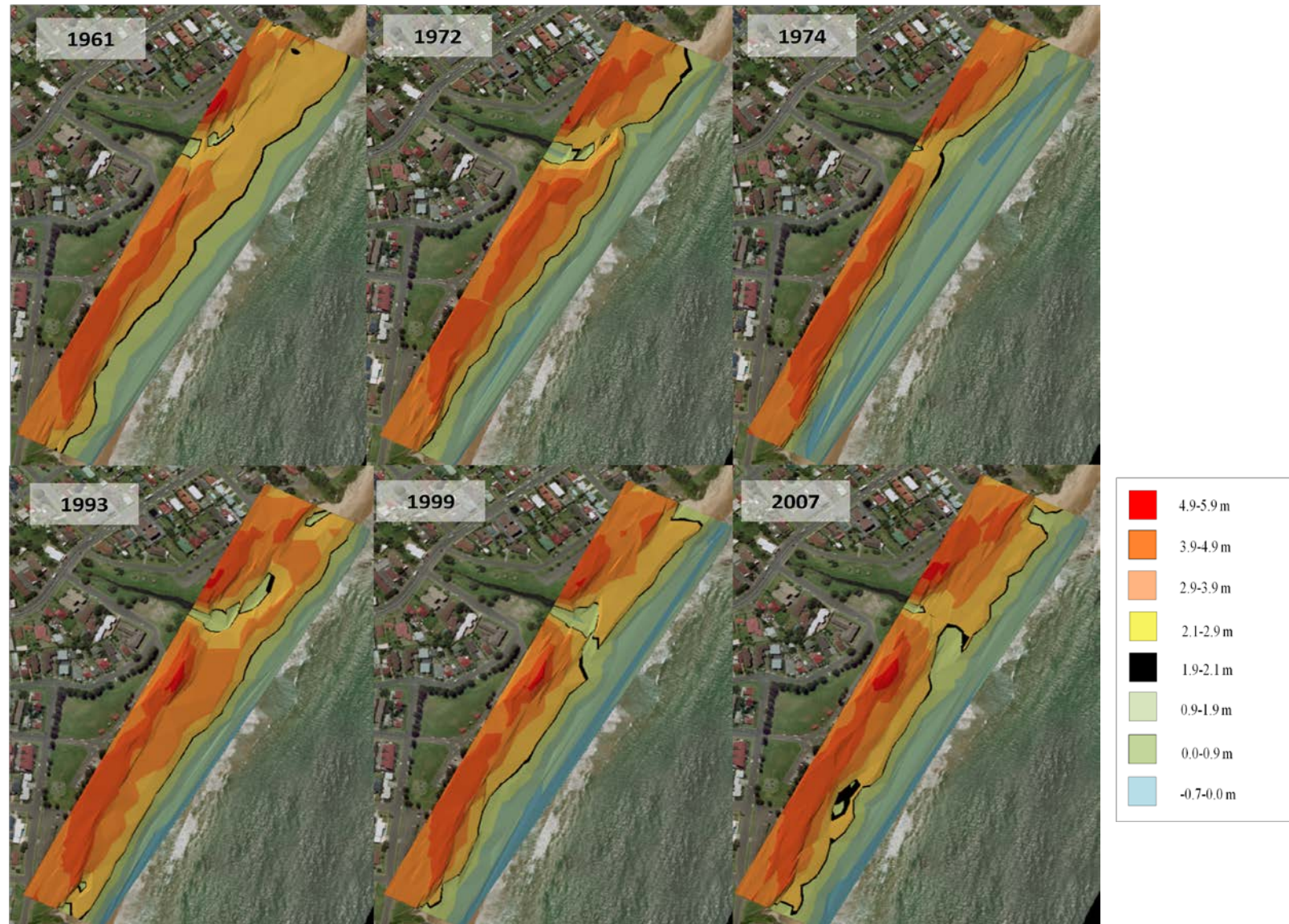


Figure 22: Tracking of the 2 m contour across Thirroul beach between 1961 and 2007. The 2 m contour is shown by the bold black line. Note the considerable landwards shift in 1974.

## 5.3 Vegetation line:

Tracking of the vegetation line allowed for evaluation of seawards, landwards, or negligible change in vegetation position across the two study beaches occurring between the dates of available aerial photography. The shift in the extent of vegetation is summarised below (Table 16 and 17) and displayed in Figures 23 and 24 for Woonona/Bellambi. The changes occurring are discussed in Chapter 7.

### 5.3.1 Woonona:

**Table 16: Summary of vegetation line change between 1938—2006 at Woonona.**

| Year      | Summary  |
|-----------|--|
| 1938      | Aerial photography not available for Woonona end of beach. |
| 1951      | Vegetation line at the most landward point in time series. |
| 1951-1961 | Moderate seawards movement.                                |
| 1961-1972 | Small landwards movement.                                  |
| 1972-1976 | Seawards movement.   |
| 1976-1981 | Seawards movement.   |
| 1981-1982 | Seawards movement.   |
| 1982-1990 | Considerable amount of seawards movement.                  |
| 1990-1994 | Discrete fluctuations.                                     |
| 1994-2000 | Moderate seawards movement.                                |
| 2000-2002 | Discrete fluctuations.                                     |
| 2002-2006 | Moderate seawards movement.                                |

### 5.3.2 Bellambi:

**Table 17: Summary of vegetation line change between 1938—2006 at Bellambi.**

| Year      | Summary  |
|-----------|--|
| 1938      | Vegetation line at the most landward point in time series. |
| 1951      | Moderate seawards movement.                                |
| 1951-1961 | Moderate seawards movement.                                |
| 1961-1972 | Small landwards movement in some areas.                    |
| 1972-1976 | Small landwards movement.                                  |
| 1976-1981 | Seawards movement in northern half of beach.               |
| 1981-1982 | Discrete fluctuations.                                     |
| 1982-1990 | Moderate seawards movement.                                |
| 1990-1994 | Discrete fluctuations.                                     |
| 1994-2000 | Moderate seawards movement.                                |
| 2000-2002 | Seawards movement.   |
| 2002-2006 | Seawards movement.   |



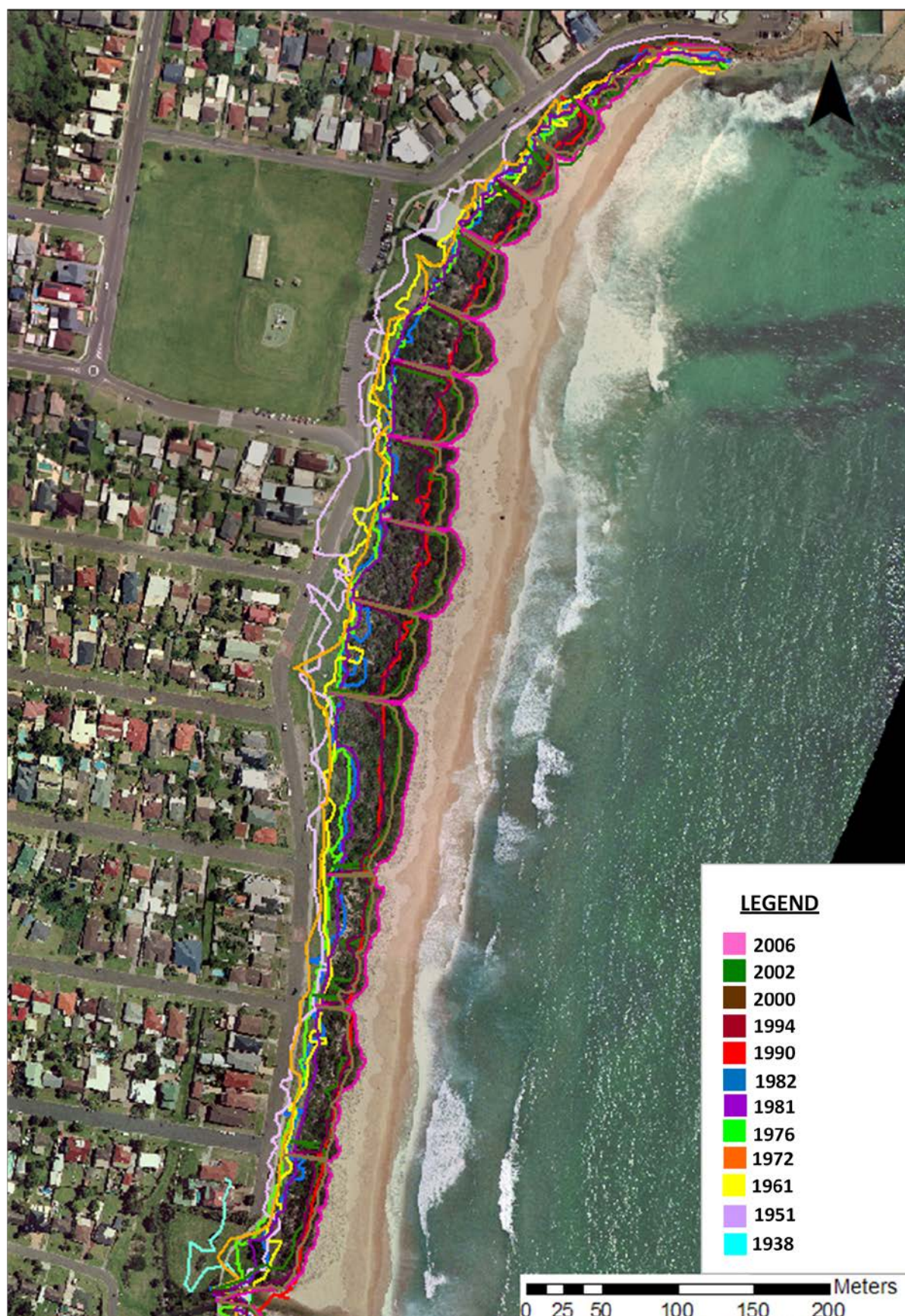


Figure 23: Tracking of the vegetation line across Woonona Beach between 1938 and 2006.



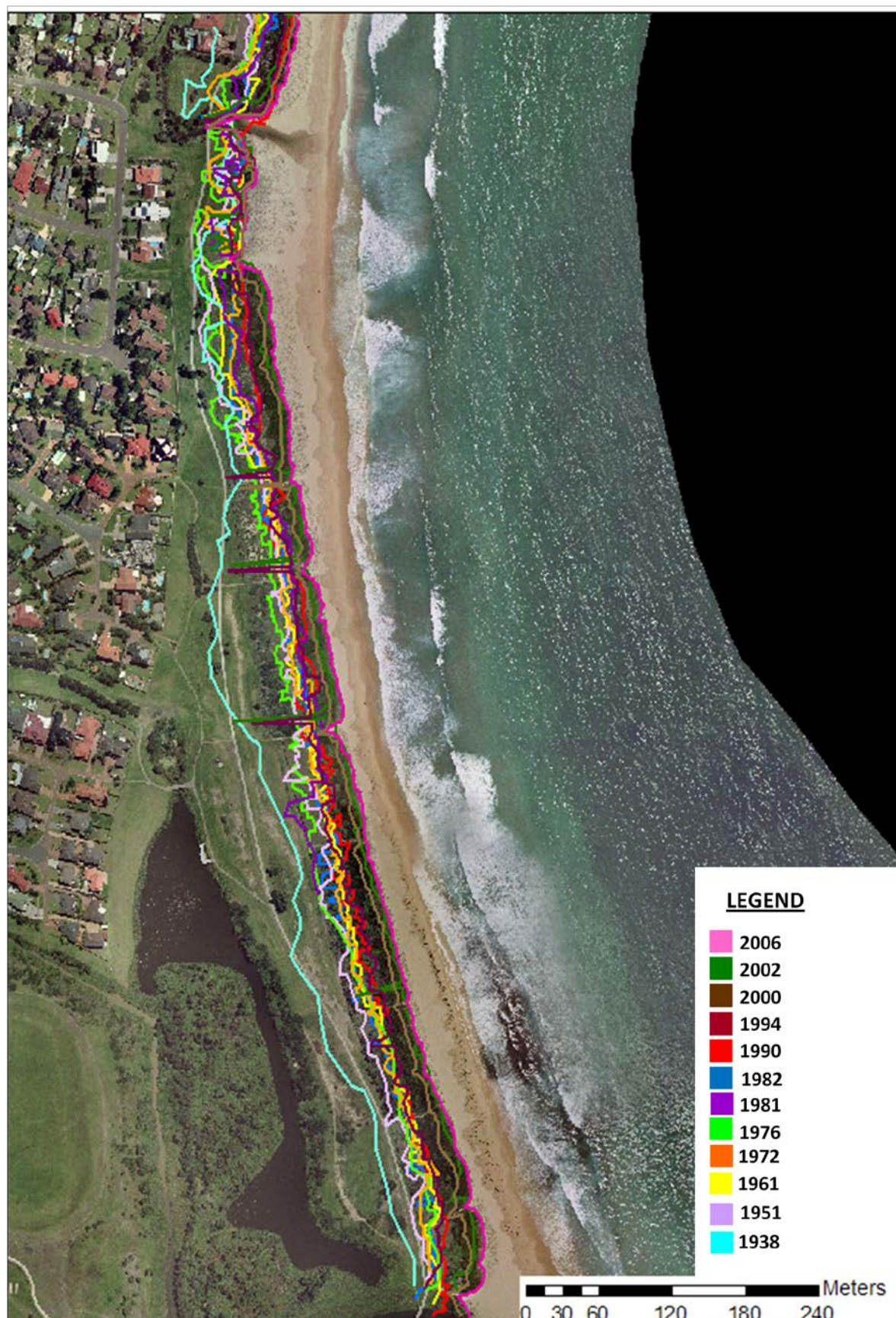


Figure 24: Tracking of the vegetation line across Bellambi Beach between 1938 and 2006.

### 5.3.3 Thirrourl:

The shift in the extent of vegetation between the available years of aerial photography for Thirrourl Beach (1961—2006) is summarised below (Table 18) and displayed in Figure 25. The changes occurring are discussed further in Chapter 7.

**Table 18: Summary of vegetation line change between 1961—2006 at Thirrourl.**

| Year      | Summary   |
|-----------|---|
| 1961      | Vegetation line generally at the most landward point in time series.  |
| 1961-1976 | Vegetation line does not move in northern and southern extents. Seawards movement at central areas either side of surf club.  |
| 1976-1982 | Vegetation line continues to remain generally stable. Small seawards movement of the vegetation line surrounding creek inlet. |
| 1982-1990 | Vegetation line continues to remain generally stable. Seawards movement of vegetation surrounding creek inlet continues.      |
| 1990-1994 | Vegetation line continues to remain generally stable. Seawards movement of vegetation surrounding creek inlet continues.      |
| 1994-2000 | Vegetation line continues to remain generally stable. Seawards movement of vegetation surrounding creek inlet continues.      |
| 2000-2002 | Vegetation line continues to remain generally stable. Seawards movement of vegetation surrounding creek inlet continues.      |
| 2002-2006 | Vegetation appears to have not had any considerable movement.   |



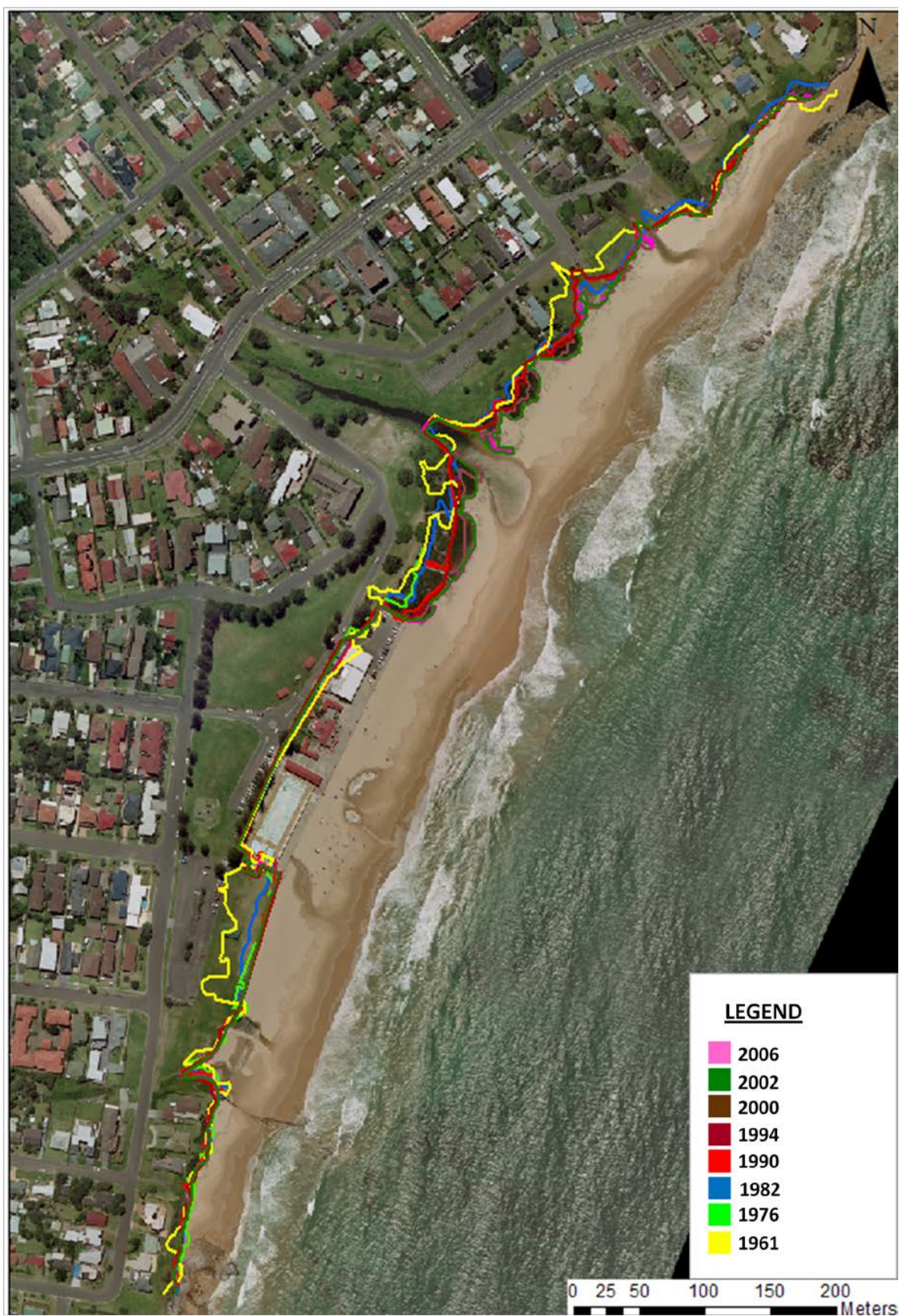


Figure 25: Tracking of the vegetation line across Thirroul Beach between 1961 and 2006.

## 5.4 Dune Change Comparison

**Table 19: Beach change direction for Bellambi and Woonona where A=Accretion; increase in dune volume, seawards movement of 2m contour, or seawards movement of vegetation line. R=decrease in dune volume, landwards movement of 2m contour, or landwards movement of vegetation line. S=Stable conditions with relatively little change.**

| Year        | Bellambi      |               |                          |                   | Woonona       |                          |               |                          |                      |
|-------------|---------------|---------------|--------------------------|-------------------|---------------|--------------------------|---------------|--------------------------|----------------------|
|             | Block One     | Block Two     |                          | Block One and Two | Block Three   |                          | Block Four    |                          | Block Three and Four |
|             | Volume Change | Volume Change | 2 m AHD Contour Movement | Vegetation Line   | Volume Change | 2 m AHD Contour Movement | Volume Change | 2 m AHD Contour Movement | Vegetation Line      |
| 1938 - 1951 | ND            | ND            | ND                       | A                 | ND            | ND                       | ND            | ND                       | ND                   |
| 1951 - 1955 | ND            | ND            | ND                       | A                 | ND            | ND                       | ND            | ND                       | A                    |
| 1955 - 1961 | R             | R             | A                        | R                 | A             | A                        | R             | S                        | R                    |
| 1961 - 1964 |               | A             |                          |                   |               | A                        | A             | R                        |                      |
| 1964 - 1966 | A             | R             | S                        |                   | R             |                          | S             | A                        |                      |
| 1966 - 1972 |               |               |                          |                   | R             | R                        |               |                          |                      |
| 1972 - 1974 | A             | R             | S                        | A                 | S             | A                        | A             | S                        | A                    |
| 1974 - 1976 | A             | A             | S                        | A                 | A             | A                        | A             | A                        | A                    |
| 1976 - 1981 |               |               |                          | S                 |               |                          |               |                          | A                    |
| 1981 - 1982 |               |               |                          | A                 |               |                          |               |                          | A                    |
| 1982 - 1987 |               |               |                          | S                 |               |                          |               |                          | A                    |
| 1987 - 1990 | A             | A             | R                        | A                 | A             | A                        | S             | S                        | S                    |
| 1990 - 1993 |               |               |                          | A                 | R             | S                        | A             | A                        | A                    |
| 1993 - 1999 | R             | R             | A                        | A                 | R             | R                        | R             | R                        | S                    |
| 1999 - 2000 | A             | A             | R                        | A                 | A             | A                        | A             | A                        | A                    |
| 2000 - 2001 |               |               |                          | A                 |               |                          |               |                          |                      |
| 2001 - 2002 | R             | R             | R                        | A                 |               |                          |               |                          |                      |
| 2002 - 2007 |               |               |                          | A                 |               |                          |               |                          |                      |

Comparison of the direction of change occurring at each dune area over the available time series of data is condensed into Tables 19 and 20. This allows for an overall interpretation of the net trend in sediment accumulation occurring across the beach areas at specific time periods. This allows evaluation of any historic trends that may be occurring in specific areas, as well as a comparison of what trend the different change detection techniques show.

**Table 20: Beach change direction for Thirroul where A=Accretion; increase in dune volume, seawards movement of 2m contour, or seawards movement of vegetation line. R=decrease in dune volume, landwards movement of 2m contour, or landwards movement of vegetation line. S=stable conditions with relatively little change.**

| Thirroul    |               |                          |                 |
|-------------|---------------|--------------------------|-----------------|
| Year        | Volume Change | 2 m AHD Contour Movement | Vegetation Line |
| 1961 - 1966 | R             | R                        | A               |
| 1966 -1972  |               |                          |                 |
| 1972 -1974  |               |                          |                 |
| 1974 - 1976 | A             | A                        |                 |
| 1976 - 1981 |               |                          |                 |
| 1981 - 1982 |               |                          |                 |
| 1982 - 1987 |               |                          |                 |
| 1987 - 1990 |               |                          |                 |
| 1987 - 1993 |               |                          |                 |
| 1993 - 1994 | R             | R                        |                 |
| 1994 - 1999 |               |                          |                 |
| 1999 - 2000 | A             | A                        |                 |
| 2000 - 2001 |               |                          |                 |
| 2001 - 2002 |               |                          |                 |
| 2002 - 2007 |               |                          |                 |

Both Table 19 and Table 20 show that generally when the volume change accretes, so too does the 2 m AHD contour move seawards. The converse is also evident- when the volume change receded, so too does the 2 m AHD contour move landwards. This infers that both change detection techniques are consistent with each other in detecting the direction of dune change.

## 5.5 Large Storm Events

The following section includes basic observations taken the day following each of the two large storm events that occurred throughout the reports year of research.

It was found that there was a general trend of increased dune cut at the northern ends of beaches, especially those with a southern aspect. Southern portions of the observed beaches were less exposed to the direction of swell during the storm due to protection from the headland. Within the study area the northern portion of the beaches generally have a steeper

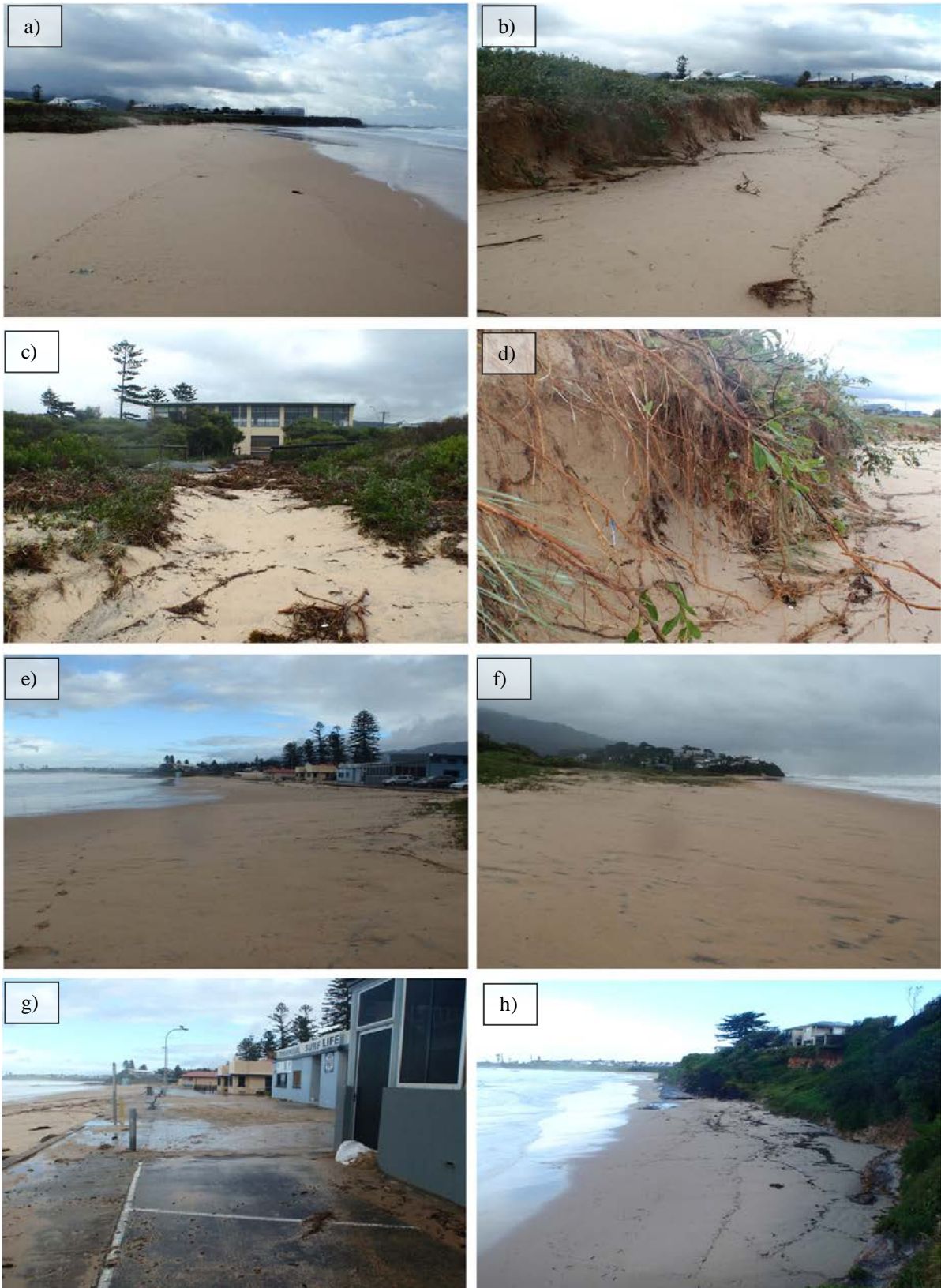


nearshore slope compared to southern portions; therefore less dissipation of wave energy occurs prior to waves reaching the shoreline. Furthermore, the dune cut was noticeable in many of the northern ends of beaches in the form of cliffing of the dune face. This was responsible for exposing roots, undercutting beach access ways, and deposition of seaweed and debris onto high areas of the frontal dune and dune face. Figure 26 compares southern ends of beaches after the large storm that occurred in June (inset b) and c)) to northern ends (inset a) and d)).



**Figure 26: Photographic evidence of storm damage: a) the location of the scarp at the northern end of South Beach, b) gentle sloping beach face at North Beach and c) south Fairy Meadow beach, and d) scarp undercutting at north Fairy Meadow beach.**

Figure 18 shows a series of further observations taken after the storm event that occurred on the 5<sup>th</sup> of June. Once again, the photographs can be categorised as either; southern ends incurring little storm cut (Figure 27 a), e), f) and g)), or northern ends that underwent considerable storm cutting, beach access way damage, or exposure of vegetation roots (Figure 27 b), c), d), and h)).



**Figure 27: Photographic evidence of storm damage: a) gentle sloping beach face at southern extent of Woonona Beach, b) scarp undercutting at northern Woonona Beach, c) storm damage to beach access ways perpendicular to Woonona SLC, d) prominent undercutting at Woonona Beach, e) gentle sloping beach face at south Thirroul beach and f) north Thirroul Beach as well as the g) SLC damage. h) Undercutting of bluffs at McCauley's Beach**



## **6.0 Discussion**

### **6.1 Introduction**

The use of GIS such as ArcMap allowed for quantitative analysis on a range of beach parameters using data from historic aerial photography. This study used ArcMap interpretations of the dune volume, 2 m AHD contour location, and vegetation line as proxies to indicate coastal erosion or accretion. These proxies provided results for Woonona/Bellambi Beach and Thirroul Beach that are able to indicate dune change in a way that is somewhat comparable to similar coastal erosion-accretion studies at similar high energy beaches of the southeastern coast. However, there are a range of factors that limit the use of these methods that must be understood before management options are considered. An explanation of the results and limitations, and their management implications are discussed in this chapter.

### **6.2 Volume Change**

The use of dune volume change as an indicator of the erosion-accretion processes occurring at Woonona/Bellambi and Thirroul facilitated a range of useful insights. The results, although temporally sparse, were compared to the accretion dominated periods (ADP) and erosion dominated periods (EDP) of McLean and Shen's (2006) beach change analysis at Moruya. This section examines the cause of the dune changes in the two WCC beaches and compares the results to those reported in the wider literature. It is fundamental that care is taken in interpretation of this reports erosion-accretion periods due to the inherent limitations in having minimal photogrammetric data sets between 1955 and 2007. The temporal resolution is so sparse that the results cannot show short-term trends as they most likely completely miss significant events, as well as introducing a likelihood of temporal aliasing.

#### **6.2.1 Woonona/Bellambi**

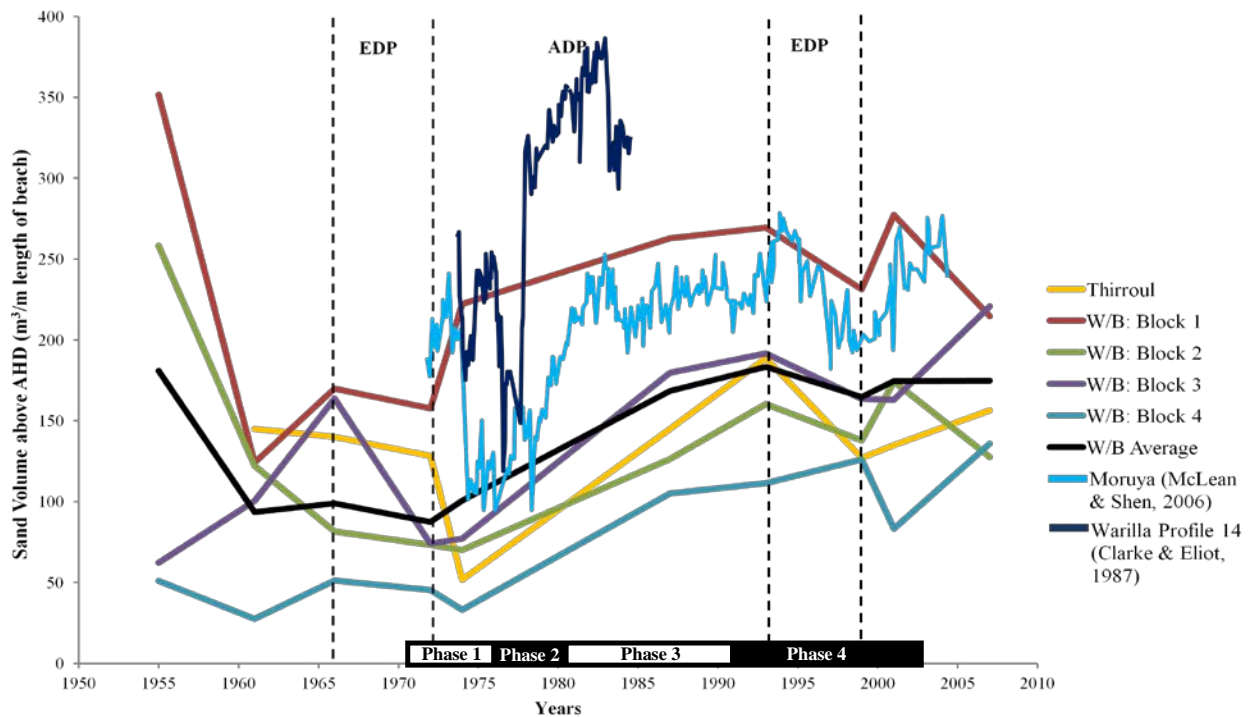
Dune behaviour at Woonona/Bellambi Beach is characterized by an erosion period (negative volumetric change) between 1966 and 1972. It was expected that all profile volumes would be at their lowest in the subsequent 1974 photogrammetric data due to the large storms that occurred approximately 5 months before the 1974 aerial photography was taken (Evans and Hanslow, 1996). Instead, only the northern portion of the beach shows a decrease in dune volume after the 1974 storm events, though the whole of Woonona/Bellambi Beach in 1972

appears to already be considerably eroded of sediment. The dunes do not appear to be further reduced in volume, but instead, undergo a small increase. Bryant and Kidd (1975) identified that beaches with a lagoon along a boundary were much less eroded after the 1974 storms, perhaps explaining a lack of erosion at the southern end of Woonona/Bellambi Beach where Bellambi Creek is located. An increase in dune volume after such a large storm period does not agree with wave impact theory (Overton *et al.*, 1987) which implies that dune face erosion is the proportional dune response to large swash waves occurring during a large storm (Larson *et al.*, 2004). It is possible that estimated vertical errors in the early photogrammetric data are so large (Hanslow, 2007) that the early photogrammetric data sets are not accurate, however, it is also likely that the aspect and openness of Woonona/Bellambi contributed to a lack of erosion. Woonona/Bellambi Beach is a 2 km long open beach with a southern end facing northeast (Short, 1993), which according to Bryant and Kidd (1975) were not badly eroded by the 1974 events.

### **6.2.2 Thirroul**

The erosive nature of the 1974 storm events were identifiable at Thirroul where all dune volumes calculated from the 1974 data set were considerably lower than any other year of data. In fact, the average change in volume between the 1972—1974 time step was an average loss of  $\sim 77 \text{ m}^3/\text{profile}$  of sediment from the dune. This considerable storm cut agrees with Bryant and Kidd (1975) as they conclude that after the 1974 storm events-erosion was higher at pocket beaches, with seawalls, wave energy intensified by refraction, and an inlet mouth—all of which are conditions met by Thirroul beach (Short, 1993). Larger beaches, similar to Woonona/Bellambi, were able to accommodate and absorb more of the storms wave energy, whilst smaller pocket beaches including Thirroul were forced by their spatial confinement to forfeit a larger amount of sediment from their backshore in attaining an equilibrium profile (Bryant and Kidd, 1975).

Post 1974 dune volumes at both study beaches showed similar trends of erosion and accretion with similar studies (Figure 28) including Moruya (Thom and Hall, 1991; McLean and Shen, 2006) and Warilla (Clarke and Eliot, 1987). From 1976 until 1993 all dunes appear to accrete (positive volumetric change) considerably. From 1993 onwards both Wollongong beaches studied appear to display similar conditions of McLean and Shen's *Phase 4*—undergoing large variations in dune volume change, however, this is based on only four data points.

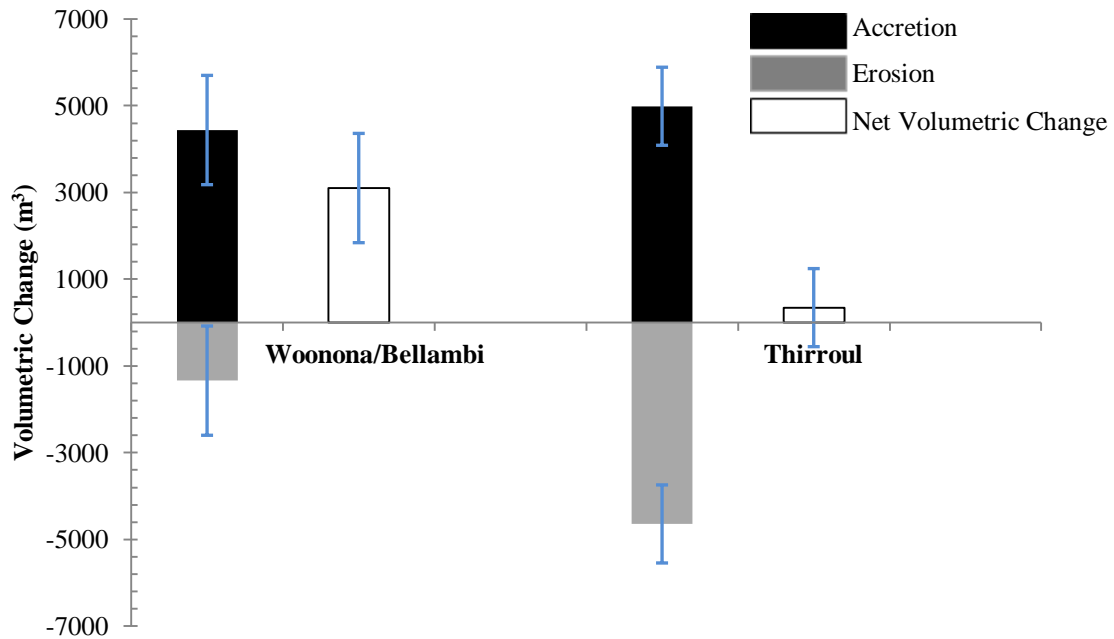


**Figure 28: Time series of dune volume change at Thirroul and Woonona/Bellambi (W/B) in cubic meters per meter length of shoreline. EDP and ADP refer to the ‘erosion-dominated period’ and the ‘accretion dominated period’. Moruya data from McLean and Shen (2006) and Thom and Hall (1991) showing the four morphodynamic conditions, and Warilla data from Clarke and Eliot (1987).**

LiDAR data was incorporated into the volume change analysis and compared to the volumes collected from the photogrammetric data. The LiDAR data set was limited in that it was a conglomeration of various sets of LiDAR data compiled over a few years between 2005-2007 (Miner *et al.*, 2010) thus specific dating of the data was not possible. Miner *et al.* previously used the LiDAR to recognise landslides within the Illawarra region. Horizontal and vertical accuracies of the dataset were determined to be <0.5 m and 0.23 m respectively. This is similar to the photogrammetric accuracies estimated in Hanslow (2007). However, the average point spacing of 2.0 pts/m means that unlike the available photogrammetric data-LiDAR can provide a high number of profiles across the entire dunes and beach system. The LiDAR used in this report was useful in providing an additional perspective on dune development within the systems. This additional perspective provided very similar volumetric levels to the 2001 photogrammetric data. The resulting similar volumes may suggest that both data sets are similarly accurate at presenting volumes at their respective profiles, therefore reinforcing the photogrammetric volumes. However, the coastal zone is highly variable at the study area therefore it would be necessary to validate this statement with data sets taken at the same time.

The Moruya and Warilla studies highlight the high short-term variability of beach volume change between 1972 and 2004 (Clarke and Eliot, 1987; Thom and Hall, 1991; and McLean and Shen, 2006). This emphasizes the importance of high frequency monitoring to ensure that these short-term events are not missed. The low temporal resolution in this report is assumed to miss a large amount of variability, particularly between the large 1974 and 1993 void of data. Despite the existence of a low temporal resolution, the volumes of both Woonona/Bellambi and Thirroul suggest similar morphodynamic phases of EDP and ADP, as well as similar dune profile volumes of approximately  $140 \text{ m}^3$  (Figure 28), to those in Clarke and Eliot and McLean and Shen. Thirroul beach in particular supports one observation of McLean and Shen (2006) that the time taken for a beach to recover from a severe erosion event may take longer than 10 years during generally calm conditions.

Net dune volumetric change was calculated for the two beaches to indicate the long-term change- whether the dune experienced overall erosion or accretion. Both beaches show some variability and net increase in dune volumes from 1961 to 2007 (Figure 199). Woonona/Bellambi profiles had a total increase in dune volume of  $3103.18 \text{ m}^3$  and Thirroul profiles had an increase of  $345.50 \text{ m}^3$ . These volumes are approximated to the full length of each beach (not just the profiles); the total volume increase since 1967 is  $147,770.5 (\pm 60,000) \text{ m}^3$  for Woonona/Bellambi, and  $11,516.67 \text{ m}^3 (\pm 30,000)$  for Thirroul. Thirroul Beach experienced similar values of erosion and accretion therefore the net volumetric change is small and its  $R^2$  value is close to zero (0.093). The net accretion at Thirroul is not significant as the estimated errors are greater than the overall change. Woonona experiences generally unidirectional accretion, with a high  $R^2$  value of 0.8347, and a large net increase in volume. This reinforces the results of Cardno (2010) as the findings show that there is no evidence of long-term shoreline recession or loss of beach volume at either beach. Additionally to the Cardno report—the results indicate that the dunes at Woonona are in fact accreting upon 1961 levels and by approximately how much.



**Figure 29: Volumetric changes at each beach since 1961, including accretion (black), erosion (grey), and net volumetric change (white).**

Analysis of coastal embayment rotation from the dune volumes was possible in this report due to south to north spread of photogrammetric blocks at Woonona/Bellambi Beach (refer to Appendix B and C for location of blocks). All blocks have undergone net volume accretion since 1966 (Figure 30). Because neither beach end is depleting in sediment it is inferred that coastal embayment rotation is not occurring. It is likely that there is a dominance of cross-shore sediment exchange, however, it is noted that a relatively large net accretion at Block Four on the northern extent of the beach may provide evidence for discrete long-shore transport. A comprehensive analysis of thirty years of beach survey measurements at the morphologically similar Collaroy-Narrabeen Beach supports this assumption (Harley *et al.*, 2011). Harley *et al.* found that cross-shore processes were accounting for ~60% of the overall shoreline variability. The shoreline oscillations were not occurring uniformly alongshore Collaroy-Narrabeen Beach as significantly larger oscillations were occurring at the exposed northern end and centre of the embayment than the more sheltered southern end. This is similar to the quantitative findings at Woonona/Bellambi Beach as the most net accretion, as well a large variability, occurred at the more exposed northern end. Similar to Collaroy/Narrabeen, it is most likely that this trend is associated with wave height and storm variability from the southerly waves dominating the wave climate along the southeastern coast (Short and Woodroffe, 2009). Harley *et al.* (2011) infer that this southerly direction would explain the volume distribution as the waves would remove/return significantly more sediment cross-shore at the northern end than at the protected southern end.

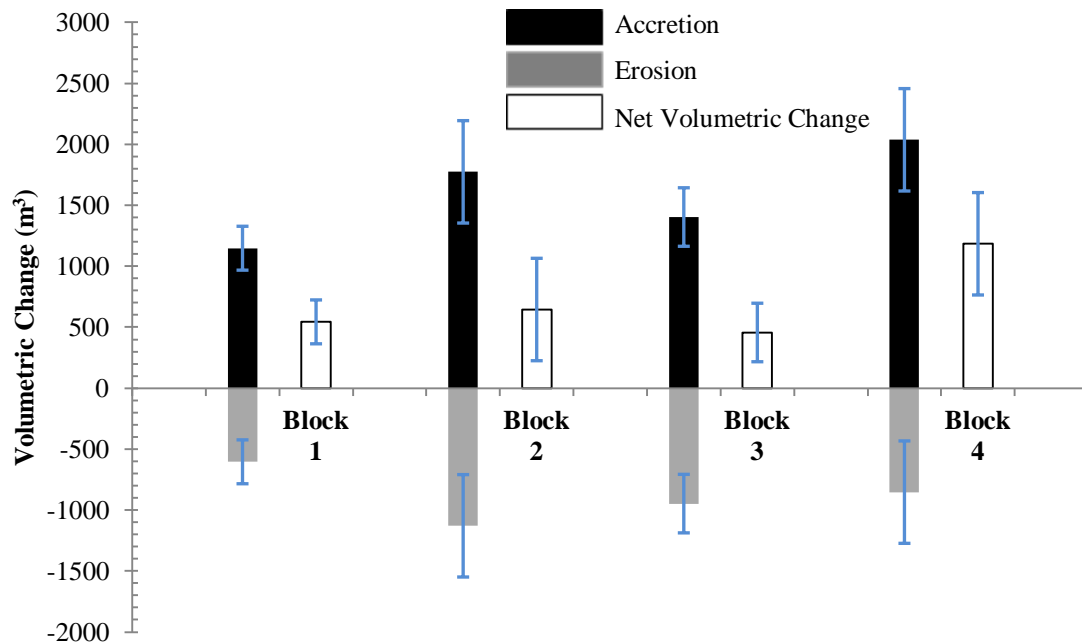


Figure 30: Volumetric changes with estimated errors at each block along Woonona/Bellambi since 1966, including accretion (black), erosion (grey), and net volumetric change (white).

### 6.3 2 m AHD Contour Movement

The active dune face/2 m AHD contour was used to indicate the movement of the dune over time. The use of a specific contour was advantageous due to difficulties in accurately visually identifying the 2 m AHD contour or active dune face from the aerial photography (Hanslow, 2007).

Trends in the movement of the 2 m AHD contour at the northern end of Woonona/Bellambi Beach were much more prominent than at the southern end of the beach. The ArcMap TIN output of the southern end of the dune provided no evidence of change across years. This is possibly due to the protection offered by Bellambi Point and the reef at the southern extent of the beach (Short, 1993). A similar process was observed in Miot da Silva *et al.*'s (2012) research on Moçambique Beach-a high energy, intermediate beach along the south coast of Brazil. Miot da Silva *et al.* identified that foredune development is closely related to wind exposure, wave energy, and gradients of longshore transport, with sheltered beaches therefore being temporally stable with a small foredune. It is most likely that the southern end of Bellambi beach is very low primarily due to the existence of the inlet mouth of Bellambi Creek cutting across the dune, with the only areas above 2 m AHD being those behind the beach on the landward side of the creek. Therefore the 2 m contour at this area is not indicative of the existing active dune face. This highlights a limitation and the difficulty of selecting a contour that approximates the scarp.

The 2 m tracking at Block Two and Three at Bellambi was successful in identifying the movement of the active dune face. Between 1955 and 2007 there was not a large amount of net movement of the dune system across these blocks with the exception of the 1955 to 1966 time step (potentially a result of poor accuracy in the 1955 data). There appears to be localised areas of recession that may reflect dune blowout (Jungerius and van der Meulen, 1989). In the most recent time step (2001-2007) Block Three appeared to build out at a consistent distance of ~16 m whilst Block Two to the south receded by approximately the same amount. This may be indicative of some longshore sediment transport similar to the sediment movement inferred at Collaroy-Narrabeen Beach (Harley *et al.*, 2011). The low temporal resolution makes it difficult to make any conclusive statements on net movement of sediment. Schoonees (2000) found annual variations in the net longshore sediment transport rates require continual monitoring for 5-8 years in order to obtain an accurate value (within 10%) of net movement.

The time steps of data at the northern end of Woonona/Bellambi Beach (Block Four) showed a large amount of movement of the 2 m contour line. Fluctuations at Block Four were much larger than those occurring at the more southern blocks. There was a considerable amount of net seaward movement of the 2 m AHD contour at this location. This may be explained by stabilisation of the dunes with vegetation and sediment supplied aeolian transport similar to the healing of the Greenwich Dunes in Canada (Mathew *et al.*, 2010) as well as sand moving predominantly northward through longshore transportation along the east coast of Australia (Short and Woodroffe, 2009). The nature of this study is unable to indicate whether the sediment is coming from within the littoral system or external sources as it only quantifies the changes (Evans and Hanslow, 1996), however, it is clear that since 1955 the active dune face has had net growth in a seaward direction.

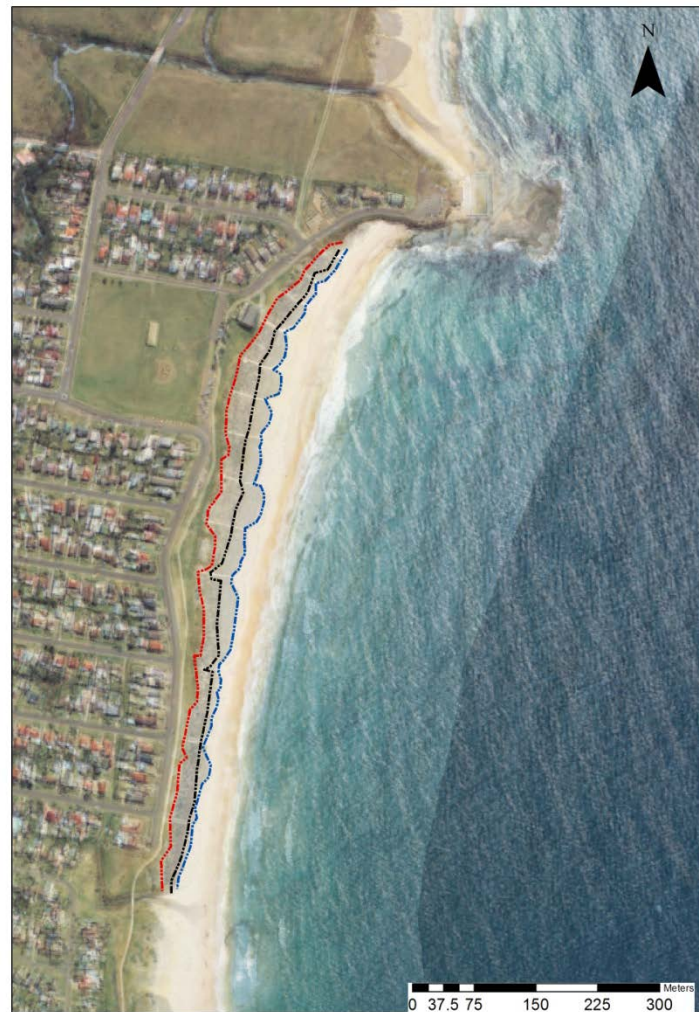
2 m AHD contour location at the Thirroul Beach experienced a large amount of change between 1961 and 2007. The 1974 2 m AHD contour was the most landward of any of the years, reinforcing the understanding that the 1974 storm event considerably eroded the beach. There is a large gap in the data set until 1993. By 1993 the 2 m contour moves to its most seawards position. From 1993 to 2007 the Thirroul system experiences large dune volume fluctuations as the 2 m AHD contour experiences minor progradation and transgression throughout these later years. Thirroul's patterns of 2 m AHD contour location is responding similarly to the accretion and erosion of McLean and Shen and additionally, generally occur in time with EDP and ADP of the dune volume in this report. However, it cannot be asserted

that the timing of the accretion-erosion periods of Thirroul are similar to Moruya as this reports historic record has too few years of data. For this reason it is suggested that the indicated long-term changes from these results are of much more importance in this report than the short-term fluctuations. Similar to the dune volume analysis, the 2 m AHD contour net movement is accretionary for both beaches since 1961 data.

## **6.4 Vegetation Line**

There was a generally consistent trend of seaward movement of the vegetation line at Woonona/Bellambi Beach. The vegetation line experienced its most landward position at the earliest time period (1938) due to the impact of early clearing of the dune system. The vegetation front progressively moves seaward until 1961—1972, at which point the vegetation line recedes inland for a short time period. From this point onwards the vegetation line continues to move seawards apart from two short periods of stability occurring at different times for the Woonona and Bellambi Beach ends (Block 1: 1982-1982, Block 2 and 3: 1990-1993, and Block 4: 2000-2002). At the Woonona end of the beach, there is a considerable seaward progression of the vegetation line from 1982 to 1990 (Figure 31); similarly, there is a large seaward progression from 1994 to 2000 at the southern, Bellambi end of the beach. This is most likely associated with the council's implementation of vegetation establishment and management in 1986. The aim of this was to stabilise and restore the natural function of the damaged dune system along Australian beaches (Bernd-Cohen and Gordon, 1999). Specifically, the vegetation establishment scheme aimed to reduce aeolian movement of sand into residential areas, as well as to provide a protective buffer to assets such as the SLC and community properties. The vegetation line is at the most seaward position in the final time slice of the monitoring period (2006). The 2006 vegetation line is approximately 40 to 70 m seawards of the 1938 and 1951 vegetation line along Woonona/Bellambi Beach.





**Figure 31: Vegetation development at Woonona Beach between 1982 and 2007. The red, black, and blue lines show the extent of vegetation during 1982, 1990, and 2007 respectively. The 2007 aerial photography is at 75% transparency overlaying the 1990 aerial photograph which is at 50% transparency overlaying the 1982 aerial photograph.**

There is an absence of large scale development of the vegetation across Thirroul Beach apart from at localised areas surrounding the creek entrance. At the creek entrance the vegetation line steadily builds in a seawards direction. This is most likely associated with sediment supply from the inlet in the centre of the beach. The sediment is likely to accumulate in existing vegetation and roots, therefore further stabilising the dune as well as increasing the area available for more vegetation to grow (Salomons, 2005; Chen *et al.* 2012). Between 1961 and 2006 the vegetation line at Thirroul builds out in an overall seawards direction, however, the rate of movement appears to be much less than at Woonona/Bellambi Beach. Vegetation growth at many areas of Thirroul Beach is restricted due to a combination of anthropogenic and geological structural bounds including the underlying sandstone outcropping at the northern and southern end of the beach, as well as the concrete edgings of the footpaths, pool, and car park.

Seawards development of the vegetation line is often associated with an increase in dune volume due to the relationship between vegetation recovery and the increased area of stabilised dunes (Hanslow, 2007). Rizzetto and Tosi (2011) were able to show that an increased amount of dune vegetation can increase the ability of the dune system to trap sediment. The relationship highlighted by Rizzetto and Tosi is not consistent with the changes in vegetation and dune volume in this report. It is evident at Woonona/Bellambi that in some of the time steps, such as Woonona/Bellambi 2001 to 2007, the dune volume experienced periods of recession despite the vegetation line continuing to move seawards, whilst the inverse occurs at other times (i.e. Woonona/Bellambi, 1966—1972). This lack of a consistent relationship is similar to the findings of Hanslow (2007) as he implies that in some cases the vegetation line may be used as an indirect measure of beach topography movement, though his study identified that the changes in the beach topography can be independent of the vegetation line. It is likely that the landward movement of the vegetation line does increase the sediment storage capacity of the dunes, however the vegetation line appears to act as a margin between two independently acting areas. This independence is further evident at Thirroul Beach as the vegetation line consistently accretes, and does not appear to recede at all, let alone in time with the recession of the dune volume or 2 m AHD contour location.

An increase in the foredune vegetation improves the protective role that dunes provide to their landward assets (Woodroffe, 2002). It is evident from the photography taken after the June 2012 storm (Figure 27: c)) that the storm surge breached the protection offered by the dune vegetation and deposited debris within metres of the SLC at Woonona- despite the large area of vegetation in the current dune system. This highlights the importance of the vegetation to dissipate the storm surge energy before it reaches and threatens the structural integrity of existing assets. The SLC and amenities at Thirroul Beach were also affected by the June storm (Figure 27, g)). This highlights the need for strategic coastal setback lines for future developments and redevelopments that take into account the increased potential of storm surge induced inundation, particularly with future predictions of SLR.

The vegetation line tracking does not appear to provide a reliable indication of dune recession or accretion. The vegetation line at Woonona/Bellambi and Thirroul has no consistent relationship with the more direct measures of beach topography; the movement of dune volume, or the 2 m AHD contour location. The vegetation line may be providing important protection by reducing the erosion of the established foredune and backshore of the beach. The foredunes are fundamental in storing sediment and protecting assets on their landward

side from extreme wave and tide conditions. The growth of vegetation on the dunes decreases the transfer of sand across the beach, therefore maintaining sand in the dune and providing more protection (Woodroffe, 2002). This relationship was studied by Heathfield and Walker (2011) at high energy and high sand supply beaches of British Columbia. They provided further evidence on the important buffer effect that vegetated dunes can have against extreme coastal conditions.

## **6.5 Limitations**

The analysis of photogrammetric data across the coastal zone is subject to a number of unavoidable limitations. It is important to be aware of these shortcomings when interpreting the results. A common mistake often made with historic photogrammetric data is overstating the inferred pattern of change despite only a few time slices of data. Fundamental to ensuring an accurate quantification of the extent of dune erosion-accretion is a long, frequently sampled, high resolution record of past beach conditions. Evans and Hanslow (1996) highlight this necessity as they state that it is not uncommon for exposed NSW beaches to experience fluctuations in dune volume of 50-100 m<sup>3</sup>/m on a monthly basis even in the absence of significant storm events. This potential variation is supported by the corresponding volume fluctuations at Warilla Beach in Clarke and Eliot (1987). Unfortunately, apart from limited examples such as at Warilla and Moruya (McLean and Shen, 2006), studies involving data at a high temporal resolution are not common along the Australian coastline. In most cases, photogrammetric analysis of historical aerial photography provides the longest, however intermittent, record of past conditions.

The photogrammetric data available for this report was not of a high temporal resolution; in fact a gap in photogrammetric data of 19 years existed in a time step within the Thirroul historic record. The historic record of photogrammetric data available in this report therefore most likely missed a large amount of potential variability in dune topography. Although the Woonona/Bellambi and Thirroul volumes may generally correspond with the patterns of sediment change of the Moruya volumes, this report is limited by the lack of a high temporal resolution. Consequently it is restricted to providing longer-term indications of past beach behaviour and, at best, speculations into short-term trends through comparison with more temporally robust studies.

Having a limited number of photographs and photogrammetric datasets across the study period is likely to have caused effects of temporal aliasing. This occurs when the sampling

rate of the study area is too low compared to the variability of the objects, such as the sediment movement, along this area. For example, the volume change at the study beaches (Figure 28) appears to jump abruptly to different volumes instead of giving the impression of changing more smoothly, generally similar to the changes in McLean and Shen (2004) and Clarke and Eliot (1987). It is understood (Fuchs, 2004) that a regular sinusoidal curve may exist in a dataset, with no overall linear trend, yet randomly choosing a few points in time may present an entirely different, and misleading sinusoid or trend line in the data (Figure 32). To avoid aliasing, it has been estimated that the sampling rate of a study area must be at least twice as high as the fastest moving object (Grant, 1985). Along the coastal zone it would be possible to detect change and avoid temporal aliasing through the use of video camera technologies (Vacchi *et al.*, 2012).

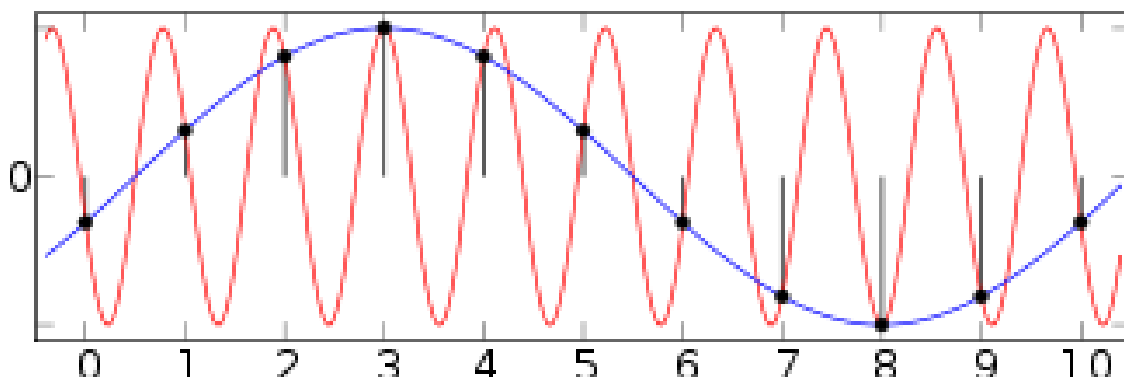
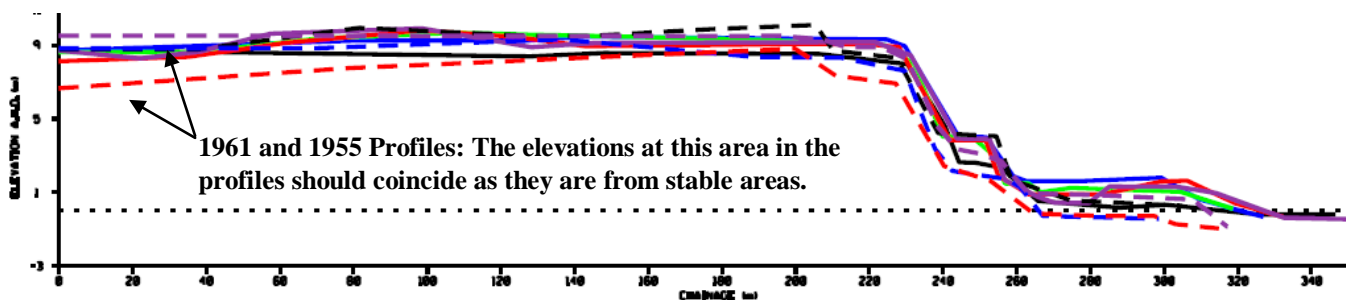


Figure 32: Two different sinusoids that fit the same set of data points.

As discussed in Chapter Three- the photogrammetric technique is limited by a number of pre-analysis factors that may hinder its accuracy. Evans and Hanslow (1996) provide the most concise summary of factors, including lens distortion, glare and shadowing, photo scale, and survey control, which were all relevant within this report. As a consequence the quantitative findings within this report are subject to varying errors based on the year of photogrammetric data collation- with year's pre 1960 being much less accurate. The estimated errors of post-1960 data, and the LiDAR data set, are 0.2 m vertically and 0.5 m horizontally (Hanslow, 2007). This equates to 30 m<sup>3</sup> and 75 m<sup>3</sup> respectively per profile per year. The differences in volume, movement of the 2 m AHD contour, and overall vegetation progression across the two beaches was almost always larger than the estimated errors estimated as shown by the error bars in Figures 29 and 30. Additionally, georeferencing the aerial photographs introduced further error to the dune change analysis. The RMS error was kept below 5 m when the photographs were 'rubber sheeted' and the residuals were evenly spread around each beach with values generally ranging from 0.2 to 8 m. It is therefore implied that the net change (overall accretion or erosion) of each indicator is valid, though the exact dune

volumes and locations of 2 m AHD contour and vegetation line should be interpreted with consideration given to the estimated errors.

Early photogrammetric data, pre-1960, can be assumed to be less reliable compared to the later data based on the reasons outlined in Chapter 3. As such, the large rates of erosion between from 1955—1961 are likely to have been misrepresented due to the low accuracy of the early photogrammetric data. The vertical accuracy of pre 1961 photography is estimated at 0.7 m (Evans and Hanslow, 1996, and Hanslow, 2007). When this is applied to the average dune length of 150 m, the inaccuracy can equate to 105 m<sup>3</sup> per profile of miscalculation. 105 m<sup>3</sup> is a considerable amount of miscalculation of the average profile volume. Therefore the earlier calculations of dune volumes are potentially very misleading, particularly when Thom and Hall (1991) have shown that monthly variation can be of a similar volume. Furthermore, the 1955 and 1961 photogrammetric data provided profiles that did not coincide with the landward extents of the following more accurate photogrammetric data (Figure 33). It can be assumed that the landward extents are stable areas, often where roads or maintained land is located. Consequently, this report has not included pre 1961 (inclusive) data into total volume calculations and regression analysis at both beaches.



**Figure 33: A representative set of profile of Woonona/Bellambi Beach (Source: Cardno, 2011). Dashed red and purple lines indicate 1961 and 1955 profiles respectively and are considered less accurate than all other years that were created from more recent photogrammetric data.**

The available photogrammetric data points provided profiles spaced at a minimum of 50 m along the dunes. The along-beach and along-dune area has a high degree of morphologic variability, particularly across high energy beaches (Theuerkauf and Rodriguez, 2012) such as the two Wollongong study beaches. Theuerkauf and Rodriguez found that at their study site, Onslow Beach, North Carolina, less than 5% of the profiles surveyed (spaced every 150 m) accurately measured the dune volumetric change to within  $\pm 10\%$  of the true volumetric change measured by RTK-GPS. Consequently, to avoid misrepresentation caused from a limited amount of dune profiles, the use of a higher number of profiles across the dune, as possible with LiDAR, will help to capture a more accurate total volume of the dune system.

In this report only one LiDAR record was available so the retrospective analysis was restricted to comparisons with the photogrammetric profiles only.

## **6.6 Management Implications & Recommendations**

The provision of a simple and legally defensible analysis of coastal morphology and associated hazards is an arduous task for coastal managers. The research within this report provides valuable insights into the monitoring and management of the continual changes occurring within the dune systems.

The primary recommendation of this report is related to future data acquisition. Two main issues must be addressed to allow for considerably more robust findings- these being spatial resolution and temporal resolution. This will equate to a significantly more realistic model of the dune topography and capture short-term variations occurring along the system. Ideally, future data might be collected similar to the high resolution data of Theuerkauf and Rodriquez (2012) using a RTK—GPS, or 3D terrestrial laser scanner (or similar remote sensor), at annual, seasonal, and storm time intervals. Though it is understood that this is a costly procedure due to the time involved in data acquisition, it would allow for a much greater understanding of the dune dynamics. This is perhaps more detail than is needed by WCC, though it would allow for strong site specific coastal management. For instance it would allow for erosion hotspots to be pinpointed, monitored, and addressed when necessary.

Site specific management of beaches within the Wollongong LGA is necessary due to the variability in fluctuations of the topography across the study sites. This variability is evident in the differing erosive effect of the 1974 storms as well as the varying net accretion occurring at the two study dunes. Woonona/Bellambi Beach appears to have a northern end more susceptible to erosion-accretion than the sheltered southern end, and Thirroul Beach was more prone to erosion than Woonona/Bellambi. Management of storm cuts should therefore be focussed on pocket beaches and the northern end of open beaches. Councils may incorporate these insights into future development and redevelopment of amenities.

The incorporation of the vegetation line as an indicator for dune change should be avoided. However, at Woonona/Bellambi Beach the suitable extent of vegetation necessary to provide adequate sediment storage and hind dune protection remains a question to be answered. It would be valuable to monitor the distance of vegetation from a designated baseline such as the bike path. This would allow for the council to act in an informed way on any unwanted vegetation growth, or to plant more vegetation where necessary. It would be advantageous to

conduct a review of alternative plant species to use in the dunes. Roze´ and Lemauiel (2004) were able to provide evidence of the ability of marram grass to heighten dune topography. Specifically, marram grass was able to increase the height of the dune rather than only increasing the seaward extent of vegetation. An ecological review of the possibility of increasing dune height may be a management approach worthwhile of consideration for Illawarra dunes.

This report reinforces Ranasinghe *et al.* (2012) in providing further evidence that the historic dependence on the Bruun Rule is unreliable and not applicable at the study area, and potentially all beaches along this high energy stretch of coastline. The simplistic assumption of a landward and upward displacement of the cross-shore sea bed profile in response to a rise in mean sea level is clearly not occurring at Woonona/Bellambi or Thirroul. The change detection techniques used in this report imply that Woonona Beach has accreted and moved seawards since the 1960s. This is despite a continual sea-level rise of 2-3 mm yr<sup>-1</sup> recorded at Port Kembla (Church et al, 2012). Newer, process based models such as the PCR model (Ranasinghe, 2012) may provide much a more robust and probabilistic estimate of SLR driven coastal change and should begin to be adapted to future coastal zone management.

## 7.0 Conclusions

The use of a range of remote sensing technologies in concert with GIS has the ability to reveal a time series of dune development which can help to establish site specific management of the coastal zone. The quantitative nature of the remote sensing data allows for a clear indication of change occurring within dunes. This data can then be combined with historic meteorological data to reveal the coastal processes that may be responsible for the change in topography. Thus, an understanding of how the beach reacts to historic conditions will allow for a pre-emptive approach to managing coastal dynamics. For example, the 1974 storm conditions and the resulting storm cut loss (such as  $77 \text{ m}^3/\text{m}$ —or  $76,719.8 \text{ m}^3$  for the whole of the Thirroul system as reported in results) has been adopted as the peak storm event for the southeastern coast and has allowed for delineation of hazard lines.

Aerial photographs, photogrammetric data, and LiDAR data for Woonona/Bellambi and Thirroul Beach provided evidence of dune topography changes, whilst allowing for a comparison of the three techniques used. The use of the vegetation line to infer an accretion or erosion event across the dune system proved unreliable as the vegetation seems to act independent of the dune volume and 2 m AHD contour location. This report infers that most erosion and accretion will occur seaward of the vegetation line, providing evidence of how net dune volume and the 2 m AHD contour can recede while the vegetation line does not. The resilience of current vegetation is highlighted. The amount of vegetation necessary to provide a barrier against erosion from storm events and the degree of protection offered poses an interesting question for future research.

The net accretion, recession, or stability of the dunes indicated through a) deriving the dune volume, and b) tracking the 2 m contour – generally appeared to correlate well with each other. Woonona (Block Three and Block Four) and Thirroul show pairing of periods with an:

- increase in dune volume with a seaward movement of the 2 m contour; or a
- decrease in dune volume with a landward movement of the 2 m contour.

EDPs and ADPs were distinguished and found to have strong similarities with comparative studies conducted at Moruya, Collaroy/Narrabeen, and Warilla. The time series of available data for the study locations was sparse, thus it is noted that considerable erosion or accretion events are likely to have been lost within the temporal constraints. Almost all profiles revealed net accretion post 1974 until 1993. This may be interpreted as a potential recovery period after the impacts of the 1974 storms. From 1993 onwards the beaches appear to



emulate Phase 4 of McLean and Shen (2004). Though the limitations in the temporal resolution of this report limits the ability of drawing conclusions centred on the short-term patterns of erosion. This renders the trend detection only useful for speculation into short-term changes based on comparisons with similar studies, while the longer-term (~50 year) patterns are more reliable. LiDAR data was incorporated into the analysis and appeared to have strong similarities with the patterns of dune sediment distribution indicated by the photogrammetric data. It is inferred that this similarity validates the integration of both technologies in future studies.

It is concluded that the combination of dune volume and 2 m AHD contour tracking are able to provide an adequate assessment of the net accretion-erosion periods at Woonona/Bellambi and Thirroul dunes. These techniques were also able to invalidate the use of the vegetation line as an erosion indicator and provided limited insights into alongshore processes. The assessment in this report is limited in its spatial and temporal resolution; as such it is recommended that future beach topography evaluations make use of higher resolution technologies, such as RTK-GPS, with much more frequent data collection. Woonona/Bellambi dune systems have accreted in volume by 147,770.5 ( $\pm 60,000$ ) m<sup>3</sup> and seaward extent whilst sea level rise has continued. Thirroul Beach dunes appear much more variable and have not experienced significant net recession since the 1960's. Coastal dunes are the first line of defence against inundation from high seas and strong waves. It is therefore necessary to continue to develop management plans parallel to the increasing understanding of the dune and beach systems within scientific literature.

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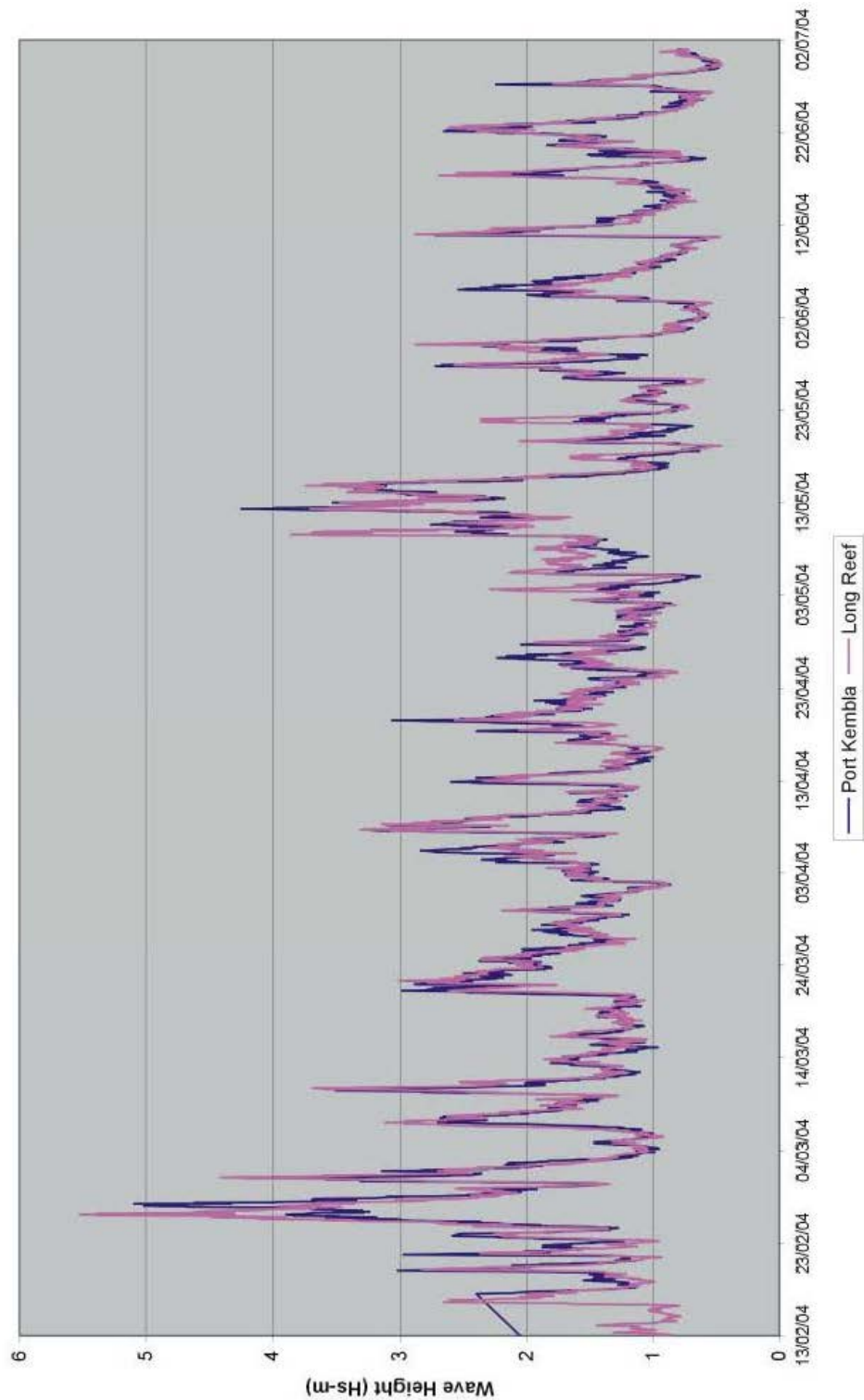
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# APPENDIX A

## COMPARISON OF OFFSHORE WAVE HEIGHTS

Long Reef (Sydney) and Port Kembla WRB's  
Wollongong CZS (Cardno, 2010)





## APPENDIX B

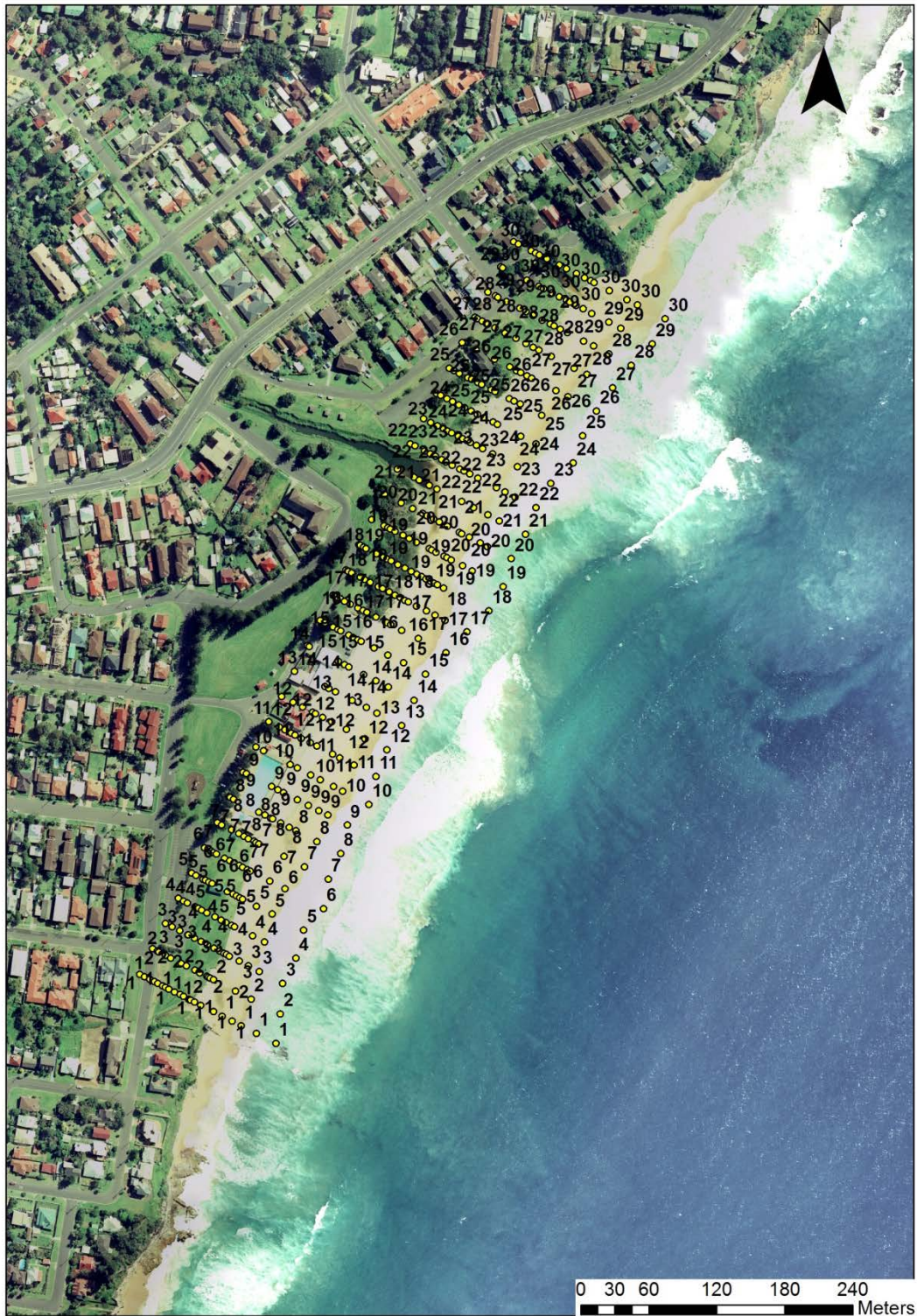
### WOONONA/BELLAMBI PHOTOGRAMMETRIC DATA POINT & BLOCK LOCATIONS





# APPENDIX C

## THIRROUL PHOTOGRAMMETRIC DATA POINT LOCATIONS



# APPENDIX D

## WOONONA/BELLAMBI PHOTOGRAMMETRIC DATA

(See additional files)

# APPENDIX E

## THIRROUL PHOTOGRAMMETRIC DATA

(See additional files)